COST COMPARISON OF B-1B NON - MISSION-CAPABLE DRIVERS USING FINITE SOURCE QUEUEING WITH SPARES

GRADUATE RESEARCH PAPER

Daniel C. Diehl, Major, USAF
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DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/IOA/ENS/12-01

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Daniel C. Diehl, BS, MBA

Major, USAF

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Approved:

//signed//	31 May 2012
Dr. Jeffery Cochran (Chairman)	date

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Abstract

Maintenance costs and maintenance man-hours have increased dramatically in the last couple of decades in relation to flying hours. These increased costs, combined with shrinking budgets, force the Air Force to streamline maintenance processes and be selective concerning which maintenance processes should receive additional funding. There are many drivers rendering an aircraft non-mission-capable (NMC). This research provides a method to compare the cost associated with any NMC driver with other NMC drivers in order to determine where limited resources are best allocated towards the goal of finding more efficient solutions that also result in reduced cost. The cost model includes lost flying time, maintenance, and parts making it more comprehensive than current methods.

Evaluation of the cost function requires estimating both number of aircraft out of service and time out of service given the behavior of the maintenance system. This is compounded by the fact that there are a small number of aircraft in a flying wing. These aircraft are split between missions and preventative maintenance. Furthermore, due to the increased age of the fleet, the aircraft prepped for missions aren't always mission capable requiring extra aircraft be prepped and ready to step into the lineup making large-number approximations unusable. Instead, a finite source queueing model including spares is incorporated resulting in simple-to-use calculations requiring no special computational resources or training. In fact, as the detailed sensitivity analyses provided in this research demonstrate, the comparison of multiple NMC drivers using the provided cost function is fairly simple provided a reliable estimate of the associated data.

The specific application of the analysis undertaken with this cost/queue formulation is the B-1B bomber. Complete maintenance data from the 28^{th} Maintenance Operations Squadron over 5 years is analyzed to define the parameters of the model and validate its results. Results obtained from this research provide multiple insights into the associated costs of NMC drivers. Certain traffic intensity ranges are dominated by specific costs while cost tradeoffs dominate crossover ranges. Furthermore, expensive parts don't always equate to the NMC driver with the highest cost. More often, NMC drivers that keep an airplane grounded the longest have the highest cost. Finally, recommendations are made among several M primary aircraft and Y spare aircraft configurations for a bomber wing.

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COST COMPARISON OF B-1B NON-MISSION-CAPABLE DRIVERS USING FINITE SOURCE QUEUEING WITH SPARES

I. Introduction

Background

Aircraft maintenance serves two masters: one preventative and the other corrective. Preventative maintenance entails all required airworthiness checks as well as standard readiness maintenance. The majority of these checks occur at the base level including daily preflight and postflight servicing and checks. However, every five years, the aircraft must go to depot for programmed depot maintenance (PDM). This check often requires the aircraft to be down for extensive periods of time. For example, a B-1B is typically down for 182 days (Park, 2010). Corrective maintenance is concerned with fixing parts once they break. As aircraft age, corrective maintenance happens more often, requiring more effort from the maintenance team. The average age of military aircraft has significantly increased over previous generations of military aircraft. The average age of military aircraft during the Vietnam War in 1973 was 9 years whereas the average age of military aircraft in 2007 was 24 years(Montgomery, 2007) and is expected to grow to 26.5 years by 2012 (Scully, 2009). This dramatic increase in average age takes its toll on the maintenance force both in terms of parts and an increase in maintenance man-hours. In the decade between 1996 and 2006 maintenance costs for the Air Force increased 38 percent and maintenance man-hours increased by 50 percent when compared with actual flying hours(Montgomery, 2007).

The significant change in aircraft availability due to the dramatic increase in corrective or unscheduled maintenance has made it extremely difficult to maintain the Air

Force’s target mission capability (MC) rate of 70 percent. The mission capability rate is based on two factors: Total Non-Mission Capable due to Supply or TNMCS and Total Non-Mission Capable due to Maintenance or TNMCM(Parson, 2010). TNMCS is based on part availability. If the part is available when needed, the aircraft is never down for supply. From July 2008 to June 2009, the monthly TNMCS for the B-1 averaged 13.7 percent while the Air Force target was 8 percent(Parson, 2010). TNMCM is based on maintenance personnel availability. If maintenance personnel are not available to service the aircraft then it is down for TNMCM. In 2008, the B-1 averaged a MC rate of just over 40 percent(Park, 2010).

As with any system, aircraft parts each follow their own bathtub curve of break-in, steady state, and wear-out independent of other parts on the aircraft. Therefore, as the aircraft ages, certain systems or the parts they contain seem to break at a higher rate than other systems. When this happens, that system or its parts drive the corrective maintenance during daily aircraft production. These parts are the non-mission capable drivers. In other words, the parts that break at a higher rate are responsible for a higher percentage of late takeoffs or cancelled missions. The parts that drive the highest number of late takeoffs or cancelled missions are rank ordered and called the NMC drivers.

One specific NMC driver currently driving mission effectiveness are certain hydraulic lines located in the main wheel wells of the B-1B. These lines are wrapped with an anti-chaffing material to prevent wear. Due to the high operations tempo in a desert environment, this wrap slowly collects sand. When the airplane has engines running, these hydraulic lines vibrate at a high rate. The sand in the wrap then slowly wears through the hydraulic lines eventually creating a hole in the line and loss of the hydraulic

system. The shape of these hydraulic lines is unique to each aircraft and thus not easy to replace.

These hydraulic lines are not the only NMC driver. In an era of shrinking budgets and fewer resources including manpower, Air Force maintenance must tackle these NMC drivers more efficiently than in past years. “Over the last several decades, total flying hours have dropped nearly 75%. Likewise, flying programs in particular have seen nearly 10% cost growth in recent years, specifically on reparable and consumable parts (Van Dyk, 2008).” In order to accomplish this, maintenance must find more cost effective fixes because they are not going to get more manpower. Sometimes the way we have been fixing the system is not the most efficient. However, with the previously mentioned resource limitations, these NMC drivers can’t be approached with the age-old method of “try something and if it doesn’t work try something else.” There has to be a better way to analyze the current fix versus proposed fixes that might improve the process and reduce total cost.

One such proposal is called High Velocity Maintenance (HVM). The goal behind HVM is to get the aircraft to the depot every 18 months vice the current 5 years (Scully, 2009). Allegedly the shortened time between visits to depot would increase visibility on all aircraft systems allowing the depot to understand the current state of all systems on the aircraft better and preferably fix systems before they show up as unscheduled maintenance. For the B-1B, unscheduled maintenance currently causes the largest delays (Scully, 2009). These delays are annotated as TNMCS or TNMCM.

Much research has been accomplished concerning the logistics and benefit to cost ratio of differing stock levels in order to improve the TNMCS metric. This paper is

specifically concerned with the TNMCM metric. However, TNMCM is not inspected as a whole. Instead, this paper models one specific NMC driver, hydraulic line chaffing, using a queuing model and attempts to lay the groundwork for comparing NMC drivers by their total cost to another NMC driver in order to determine where maintenance can get its best benefit to cost.

Problem Statement

The purpose of this research is to compare the total cost associated with an NMC driver with other NMC drivers in order to determine where limited resources are best allocated towards finding a better solution.

Research Objectives

To understand how a cost comparison approach may be beneficial to determining which NMC requires a better solution over another NMC driver, this research effort has set forth the following research objectives:

- Determine the total cost associated with a generic NMC driver to include cost of lost training, cost per maintenance hour, and parts cost.
- Determine a ratio range for individual cost determination in the total cost function.

Comparison of total cost should provide valuable insight into which NMC driver should be explored for a better solution.

II. Literature Review

Overview

This chapter provides a discussion of completed research concerning queueing and corrective maintenance along with its associated cost. Much research has looked at maintenance in terms of the balance between preemptive and corrective. Researchers have also looked at the use of new technology to reduce the cost of corrective and preemptive maintenance. Finally, the cost of the logistic pipeline behind maintenance has been researched. However, none of these studies have combined a cost perspective with corrective maintenance in order to determine which corrective maintenance item should be tackled first when capital is tight.

	Teal & Sorensen, 2001 alking and Reneging AND Machine Repair Problem with Warm Spares, 1994

Table 1: Article Comparison

Cost Considerations

One aspect of preemptive or Time Based Maintenance (TBM) explored is the switch to Condition Based Maintenance (CBM). This move is based on airline management stressing cost reductions, prudent use of existing capital and an intelligent use of new technology (Teal & Sorensen, 2001). Specifically, the authors looked at aircraft wiring. In order to transition to CBM, a significant investment in the technology

to support diagnostics and inspection as well as the tools and personnel training to conduct proper diagnostics and inspection must be made. In doing so, the US Navy achieved an 88% reduction in wire events in one type aircraft (Teal & Sorensen, 2001). This study ultimately looked at the associated cost reductions in corrective maintenance by changing preemptive maintenance utilizing new technology.

Another study looked at proper maintenance staffing in order to handle reactive maintenance at the lowest cost. The authors of this study maintain that maintenance labor contributes as much as 80% of the total maintenance cost associated with a production line (Chang, Ni, Bandyopadhyay, Biller, & Xiao, 2007). Although this study specifically addresses reactive maintenance or corrective maintenance and its associated cost, it does not address a comparison of specific corrective maintenance items and their associated costs nor does it address any type of process improvement to reduce the occurrence of reactive maintenance items.

Another class of research aimed at reactive maintenance looked at cycle time reduction for naval aviation depots (Kang, Gue, & Eaton, 1998). The authors ran two simulation models utilizing material availability and process redesign to illustrate a significant reduction in cycle times by increasing stock levels of relatively inexpensive parts and modifying other repair processes. In this research, reduction of cycle time replaces reduction in cost as the overall objective function. However, this research looks at the cycle time of the base and depot level maintenance as a system and does not address a method to decide which process to fix when resources are constrained.

Parts Cost

Ted Wahoske conducted similar research to the base and depot level maintenance system specifically analyzing a least cost procurement strategy for B-1B consumables and reparables(Wahoske, 2011). In order to conduct the analysis, Wahoske also collected the Federal Stock Number (FSC) cost data for parts from the Air Force Total Ownership Cost (AFTOC) database located at Ogden Air Logistics Center, Hill AFB, UT. Figure 1 shows a breakdown of unit cost by FSC.

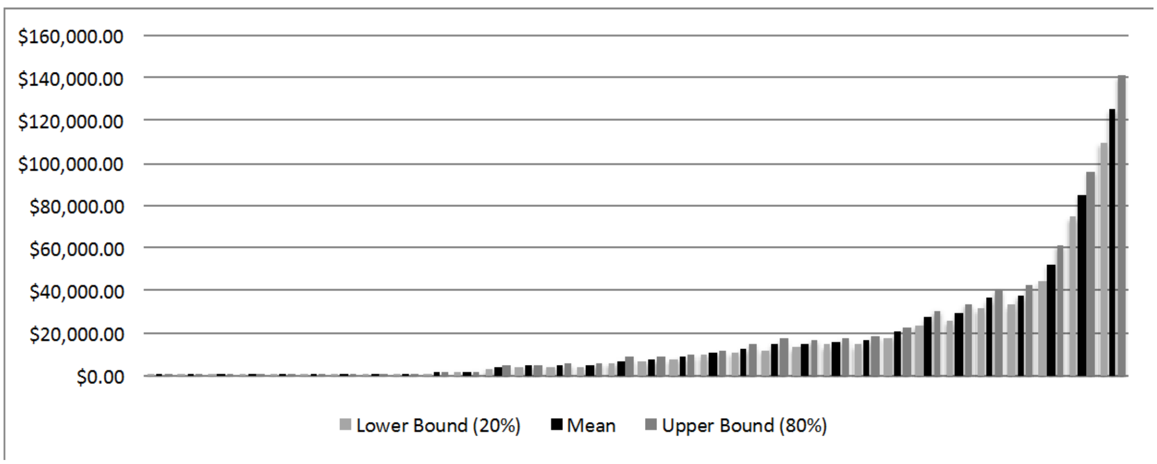

Figure 1. Unit Cost by FSC

He broke the parts down into three cost classes: FSCs with a cost below $200 per unit (Figure 2), $200 to $10,000 per unit (Figure 3), and above $10,000 per unit (Figure 4).

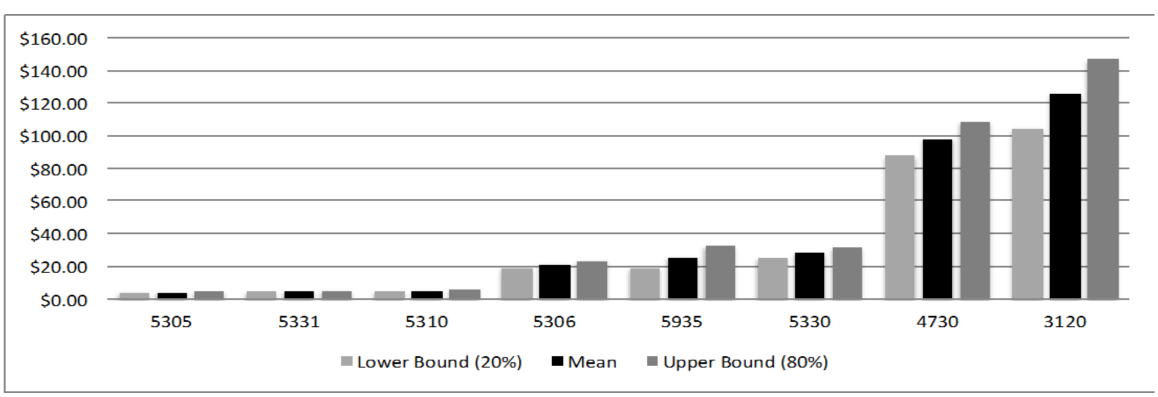

Figure 2. Unit Cost by FSC < $200

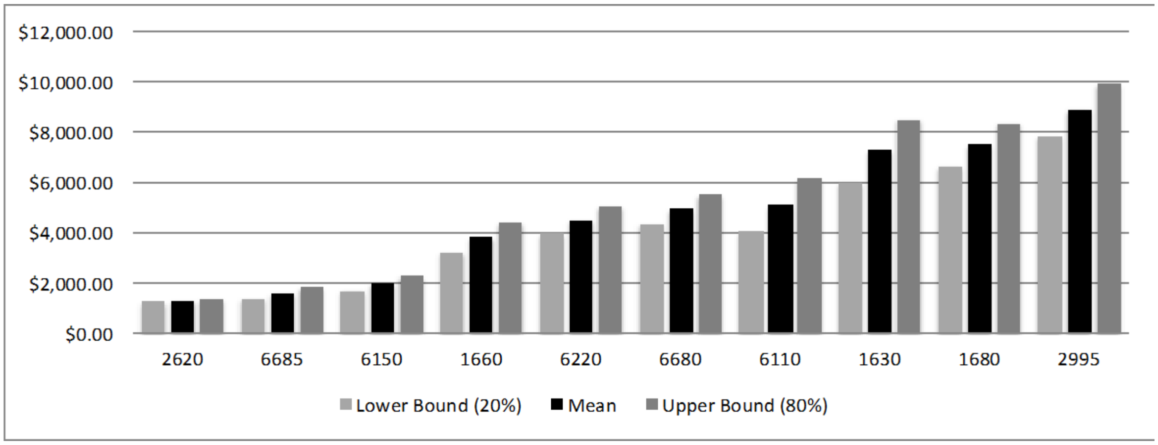

Figure 3. Unit Cost by FSC $200 to $10,000

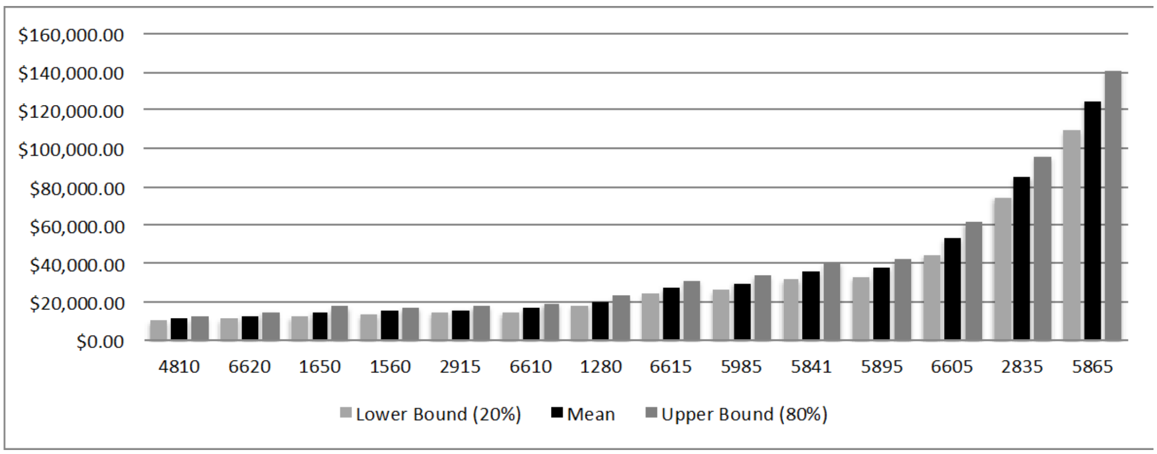

Figure 4. Unit Cost by FSC > $10,000

This research looks at cost and B-1B parts, but only to decide appropriate part levels and how those parts affect mission capability rates. It does not look at total cost comparisons nor does it look at improving the MX process or changing technology (Wahoske, 2011).

Service Facilities

Dewan and Haim take a unique approach to service facilities by stating that those facilities, when internal to an organization, should be treated as deficit centers because they do not directly contribute to profit. The use of internal pricing should be utilized. They further address the appropriate scale or capacity of the internal service facility as a

function of user demand where the internal price is a function of lost service by the other internal users (Dewan & Mendelson, 1990).

Queueing

Much research has been done in the queueing field. Two specific categories of queueing are infinite source and finite source. The source corresponds to the population that the service supports. Finite source queueing is used to analyze many types of problems including machine repairmen, time-sharing computer systems, multi-programmed computer systems and multi-access communication channels (Gupta & Melachrinoudis, Complementarity and Equivalence in Finite Source Queueing Models With Spares, 1994). Along with source, other major contributors to the type of queueing model to use are the number of servers and the number of services. The number of servers can reflect multiple servers providing the same service or multiple servers each providing a different kind of service performed in series or parallel. Whether using one or multiple servers, the most efficient queue serves the fastest jobs first (Elsayed, 1983)(Asztalos, 1980).

Queueing provides a closed form solution to determine performance parameters such as the average number in the queue or system, average time spent waiting in the system for service and the average time spent in service. It also provides the probability of the system being in any given state. As such, much work has gone into determining the math behind each type of model to include complementary models or equivalent models in order to simplify the model of more robust systems(Gupta S. M., 1994)(Gupta & Melachrinoudis, Complementarity and Equivalence in Finite Source Queueing Models With Spares, 1994).

The math behind basic queueing models is no longer adequate when more realistic bounds are placed on the model. For example, many systems experience balking or reneging. Balking occurs when a customer decides not to enter a line because it appears too long. In this case, the customer is lost to the system. Reneging occurs when a customer joins the line and at some point decides they will not wait any more and depart. Many machine repair systems also include spares. The machine repair problem has a finite source of machines that are the customers and a set number of repairmen to service those machines when they fail. Spares are used to substitute for a down machine when available. Once all spares are in service any further breakdown will short the system since it will be operating with less than the requested number of machines. As the down machines are repaired they become spares. Spares have been further identified as cold, warm, or hot. A cold spare implies that an inactive machine does not break down. A hot spare implies that an inactive machine breaks down at the same rate as an active machine and a warm spare implies that an inactive machine breaks down somewhere between a cold and hot spare(Gupta S. M., Interrelationship Between Queueing Models with Balking and Reneging AND Machine Repair Problem with Warm Spares, 1994)(Gupta S. M., 1994).

Finally, some queueing research has attempted to answer the question of optimizing a system based on total cost. Total cost is the cost of operating the system plus the cost waiting cost (the cost of something in the system not performing its primary task) and, when applicable, the cost of lost customers when balking or reneging occurs (Chang & Ke, 2011).

Maintenance Queueing Analysis

Roark, Feldman, and Bexfield explore queueing as it relates to B-1B avionics/automatic test equipment in order to determine the proper number of testers (servers). The authors determine that the arrival rate of the avionics line replaceable units (LRUs) is not constant over a maintenance day or during different days of the week because a flying wing has certain flying windows that they operate during and different numbers of aircraft are generated during each of these windows. Therefore the authors utilized a week as their time interval in order to standardize the arrival rate across data. They determined that the optimal number of testers should balance the cost of service and the cost of waiting for service in order to achieve the lowest overall cost (Roark, Feldman, & Bexfield, 1984).

Process Change

Just as using a new technology to fix a system has the possibility of decreasing fix time and therefore decreasing total cost associated with the fix, process change can also have these effects. One study looking at process change looks at High Velocity Maintenance or HVM utilizing simulation. The goal behind HVM is to get aircraft to depot for PDM every 18 months vice the current 5 years. By sending the aircraft to depot more often systems would hopefully be identified and fixed before showing up as unscheduled maintenance. This process then allows flightline maintainers to concentrate on normal flight operations thereby reducing delays associated with servicing actions. The availability of maintenance personnel to accomplish servicing was modeled as the maintenance improvement factor. The study found that as the maintenance improvement factor increases, it has the greatest affect on increasing MC rates. In other words, the

maintenance improvement factor contributed more to the increasing MC rates than part stock levels or any other factor modeled (Park, 2010).

III. Methodology

Overview

This chapter describes the origin of the data and provides an explanation of the method used to analyze the data.

Data Source

The analysis section of the 28th Maintenance Operations Squadron (MOS) Ellsworth AFB, SD provided the data concerning hydraulic line chaffing. The data covered a six year period between January 2006 and October 2011 for all assigned 28 Bomb Wing B-1Bs. In order to extract all jobs associated with wheel well hydraulic line chaffing actions and events Integrated Maintenance Data System (IMDS) output for Work Unit Codes (WUC) 13AAO and 13A99 were analyzed and further refined in order to extract only those hydraulic jobs associated with wheel well hydraulic line chaffing discrepancies actions and events. The calculated flying hours between discrepancies was extracted from 28 Bomb Wing Accomplished Utilization Report (Benson, 2011).

This data was transcribed into a table like the one shown in Figure 5. Out of the 35 reported jobs only 18 were specific to the hydraulic line chaffing issue. Interarrival times were reported as flying time accrued since last occurrence. Service time was given in both start-stop format and MX man-hours utilized. Service time was also provided with no mention of elapsed time from failure to aircraft in for service.

						Time In Service		Time In Service		
Aircraft Tail #	Jobs Reported	Jobs (Chaffing Related)	Flying Hours	λ	Time Before Service	Start - Stop Time	Total Time	MX Hours	Total Time	Servers (People on the Job)
5081	7	1	2103.7	0.00048	36	0.5	36.5	1	37	2
5085	2	1	1900.9	0.00053	36	1	37	1	37	1
6095	1	0	764.7	0						
6111	7	6	277.9	0.02159	36	0.25	36.25	1.8	37.8	7
					36	0.1	36.1	0.1	36.1	1
					36	0.3	36.3	0.3	36.3	1
					36	0.3	36.3	0.3	36.3	1
					36	0.3	36.3	0.3	36.3	1
					36	0.3	36.3	0.3	36.3	1
6113	1	0	749.4	0						
6118	1	1	140.9	0.0071	36	0.3	36.3	0.3	36.3	1
6125	4	2	1119.5	0.00179	36	1	37	2	38	2
					36	1	37	2	38	2
6127	3	3	1549.8	0.00194	36	0.5	36.5	0.5	36.5	1
					36	0.5	36.5	0.5	36.5	1
					36	1	37	3	39	3
6129	2	2	92.8	0.02155	36	3	39	9	45	3
					36	2.9	38.9	5.8	41.8	2
6130	2	2	38.6	0.05181	36	0.5	36.5	1	37	2
					36	0.5	36.5	1	37	2
6134	2	0	107.7	0						
6138	3	0	496.6	0						
Total:	35	18	9342.5	0.10678	648	14.25	662.25	30.2	678.2	34

Figure 5: Data Input Table

Cost

The desired outcome from this data is a total cost function that can be compared between specific NMC drivers. Total cost per NMC driver is a function of some hourly cost, C_1, resulting from lost aircrew training resulting from the unavailability of the aircraft for daily flying operations. This cost is analogous to lost revenue in the commercial airline industry. Total cost is also a function of the associated service costs; the cost per maintenance hour, C_2 and the cost of parts to fix the discrepancy, C_3.

Defining C1 can be a difficult task. The cost of lost training is itself hard to define because there are multiple levels of training. On a four-man crew, some crewmembers may be in a formal training course while others are only receiving continuous training. Still another crewmember may be flying because they will expire on some currency if they don't get that flight resulting in an instructor pilot who is not available to fly with students until another sortie is flown to get that aviator recurrent. Estimates for the cost of lost training range from $4,000 to $37,000 per hour (Weatherington, 2012). C2, or the cost per maintenance hour is no less difficult to define. A simple hourly rate per maintenance troop can be determined using Air Force Instruction (AFI) 65-503 and

shown in Appendix I. After incorporating basic pay, health care accrual, retired pay accrual, basic allowance for housing (BAH), basic allowance for subsistence (BAS), and any incentive pay the total annual composite rate for an E-3 is $51,994 and an E-8 is $120,488. Standardizing the annual figures to an hourly rate based on a 40-hour work-week and 52 weeks per year delivers $25 per hour and $58 per hour respectively (US Air Force, 1994). These hourly rates do not take into account organizational cost of supervision, training, or equipment associated with the maintenance troop. In order to account for the cost of supervision, training, and equipment associated with the maintenance troop, this analysis assumed a cost of $1,000 per maintenance hour since a maintenance hour is based on one maintenance troop. At $4,000 per hour, the cost due to lost training is equal to the assumed $1,000 per hour maintenance cost since there are four aviators in a crew. Therefore, doubling the cost per hour for lost training would be $8,000 per hour. C_3 is the easiest cost to estimate. All parts associated with aircraft maintenance are listed by Federal Stock Class (FSC) identifier and range from a couple cents to over $140,000 (Wahoske, 2011).

Queueing

A typical B-1B squadron has twelve primary authorized aircraft (PAA). Of these twelve aircraft a couple are usually in some type of long duration scheduled maintenance and a couple are in some type of short duration scheduled maintenance. Furthermore, a typical flying schedule for a bomb wing only needs 4-6 aircraft generated per day with a couple spares in case of unscheduled maintenance on the primary aircraft. Therefore a queueing model utilizing spares is modeled. Six models are used in order to encompass six primary aircraft with one or two spares, five primary aircraft with one or two spares,

and four primary aircraft with one or two spares. For this purpose, primary aircraft are denoted by M and spare aircraft are denoted by Y.

The average number of aircraft down for a specific NMC driver is defined as L. The average time per aircraft spent in the system, waiting for maintenance and maintenance time, is W where W_q is the time spent waiting for maintenance and W_s is the maintenance time. The queueing performance measures are calculated with five different delays: 36, 27, 18, 9, and 0 hours. μ is calculated as $\frac{18}{\sum_{j=1}^{j=18} delay_j + MX\ hours_j}$ where j is job number. λ is calculated as $\frac{number\ of\ jobs}{total\ flight\ hours}$ or $\frac{18}{9342.5}$. Closed form queueing equations for a finite population with spares is used to determine all performance parameters (Gross & Harris, 1998).

Since the model includes spares, the arrival rate must reflect this. When the first aircraft breaks a spare is available and therefore it does not affect the useable population or in this case the primary aircraft availability. Therefore λ_n is denoted as

$$\lambda_n = \begin{cases} M\lambda & (0 \le n < Y) \\ (M - n + Y)\lambda & (Y \le n < Y + M) \\ 0 & (n \ge Y + M) \end{cases}$$

For the single spare models this equation simplifies to

$$\lambda_n = \begin{cases} M\lambda & (n = 0) \\ (M - n + 1)\lambda & (1 \le n < 1 + M) \\ 0 & (n \ge 1 + M) \end{cases}$$

and for the 2 spares models this equation simplifies to

$$\lambda_n = \begin{cases} M\lambda & (0 \le n \le 1) \\ (M - n + 2)\lambda & (2 \le n < 2 + M) \\ 0 & (n \ge 2 + M) \end{cases}$$

The effective service times (μ_n) are simply μ because B-1B aircraft maintenance is modeled as a single server. For all models, the single server is less than or equal to the number of spares. Therefore, the probability of n aircraft down at any given time is

$$p_n = \begin{cases} \dfrac{M^n}{n!} r^n p_0 & (0 \le n < c) \\ \dfrac{M^n}{c^{n-c} c!} r^n p_0 & (c \le n < Y) \\ \dfrac{M^Y M!}{(M-n+Y)!\, c^{n-c} c!} r^n p_0 & (Y \le n \le Y+M) \end{cases}$$

Since there is only one server, this equation further simplifies to

$$p_n = \begin{cases} p_0 & (n = 0) \\ M^n r^n p_0 & (1 \le n < Y) \\ \dfrac{M^Y M!}{(M-n+Y)!} r^n p_0 & (Y \le n \le Y+M) \end{cases}$$

For the single spare models, this equation simplifies to

$$p_n = \begin{cases} p_0 & (n = 0) \\ \dfrac{M^1 M!}{(M-n+1)!} r^n p_0 & (1 \le n \le 1+M) \end{cases}$$

For the two spares models, this equation simplifies to

$$p_n = \begin{cases} p_0 & (n = 0) \\ M r p_0 & (n = 1) \\ \dfrac{M^2 M!}{(M-n+2)!} r^n p_0 & (2 \le n \le 2+M) \end{cases}$$

In order to get the performance parameters, L and W, we must first find the effective arrival rate or λ_{eff} where

$$\lambda_{eff} = \lambda \left(M - \sum_{n=Y}^{Y+M} (n-Y)\, p_n \right)$$

Second, the value of p_0 must be determined where

$$p_0 = (1 + a_1 + a_2 + \cdots + a_{M+Y})^{-1}$$

and $a_n \dots a_M$ are the coefficients multiplying p_0 in the p_n equations above. With these computations complete, it is now possible to determine L and W.

$$L = p_0 \sum_{n=1}^{M+Y} n\, a_n$$

$$W = \frac{L}{\lambda_{eff}(M + Y - L)}$$

Finally, the breakdown of L into subcomponents L_q and L_s and the breakdown of W into subcomponents W_q and W_s is possible.

$$L = L_q + L_s \qquad \text{and} \qquad L_q = L - \frac{\lambda_{eff}}{\mu}$$

$$W = W_q + W_s \qquad \text{and} \qquad W_q = \frac{L_q}{\lambda_{eff}(M + Y - L)}$$

L_q is the average number of aircraft waiting on service and L_s is the average number of aircraft in service. W_q is the average time per aircraft spent waiting for service and W_s is the average time per aircraft spent in service.

Cost Function

Total cost in the context of this model is a mean cost because it is time averaged. In other words, at any given point in time, the total cost provides a snapshot of the cost of that NMC driver at that exact point in time. Total cost is a function of the cost of lost training, cost per maintenance hour, and the cost of parts. In order to determine the cost function, each of these parameters must be determined. The cost due to lost training or C_1 is based on aircraft availability. An aircraft is not available for flying operations when it is broken. Therefore C_1 is dependent on the number of aircraft unavailable (L) and the length of time those aircraft are unavailable (W) resulting in:

$cost\ due\ to\ lost\ training = C_1 * L * W$. Cost due to servicing the aircraft is a function of the cost per maintenance hour, C_2, the average time it takes to fix the aircraft (W_s), and the cost of parts, C_3 resulting in: $cost\ due\ to\ service = W_s * C_2 + C_3$. Therefore the associated total cost function is: $Total\ Cost = (C_1 * L * W) + (W_s * C_2 + C_3)$.

Summary

Determining the performance parameters of this queueing model is straightforward utilizing well-known closed form equations. Determining the cost associated with the performance parameters is entirely different. Furthermore, as is usually the case, some interpretation of the data was accomplished in order to put it into useable form.

IV. Analysis

Performance Parameters

All calculations completed during the analysis are available in Appendix II. The supplied data returned an arrival rate (λ) of 0.001926679 and a service rate (μ) of 0.59602649 with no account of time the aircraft was non-mission capable before entering service. This arrival and service rate results in a baseline traffic intensity ($r = \lambda/\mu$) of 0.003232539. The cost function was initially calculated using $\$C_1$ = \$4000, $\$C_2$ = \$1000, and $\$C_3$ = \$5000 for all six models. The performance parameters are shown in Table 2.

The next step was to vary λ and μ in order to provide performance parameters for sensitivity analysis and provide a baseline for comparing the total cost of one NMC driver versus another. To this end, the same model was recalculated using λ*10 and holding μ to the original values and then again holding λ to its original value and using μ*10. These performance parameters are shown in Table 3 and Table 4 respectively.

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.07259299	0.05525288	0.03791276	0.02057265	0.00323254
L =	0.70897396	0.47937164	0.29154976	0.14061683	0.01977875
W =	8.55665763	5.55420909	3.27914533	1.54822966	0.21439956
Ws =	5.16769212	3.81321565	2.55275408	1.35860252	0.21024201
L*W*C1 =	24265.7898	10650.1213	3824.13613	870.828564	16.9622245
Ws * C2 + C3 =	10167.6921	8813.21565	7552.75408	6358.60252	5210.24201
Total Cost =	34433.4819	19463.3369	11376.8902	7229.43108	5227.20424

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.07259299	0.05525288	0.03791276	0.02057265	0.00323254
L =	0.65579865	0.45656831	0.28455199	0.13957514	0.01977504
W =	9.31047256	6.17202494	3.70204262	1.76478087	0.245084
Ws =	5.93893159	4.38268162	2.93022562	1.55643098	0.24036156
L*W*C1 =	24423.1814	11271.804	4213.6944	985.27815	19.3861866
Ws * C2 + C3 =	10938.9316	9382.68162	7930.22562	6556.43098	5240.36156
Total Cost =	35362.1129	20654.4857	12143.92	7541.70913	5259.74775

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.07259299	0.05525288	0.03791276	0.02057265	0.00323254
L =	0.54068872	0.37355955	0.23238809	0.11454711	0.01642817
W =	8.78677196	5.88015731	3.56986779	1.72731824	0.24419256
Ws =	5.83309522	4.3277802	2.90763981	1.55077348	0.24024637
L*W*C1 =	19003.6338	8786.35577	3318.37908	791.437231	16.046543
Ws * C2 + C3 =	10833.0952	9327.7802	7907.63981	6550.77348	5240.24637
Total Cost =	29836.7291	18114.136	11226.0189	7342.21072	5256.29291

5 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.07259299	0.05525288	0.03791276	0.02057265	0.00323254
L =	0.50636525	0.35870054	0.22775448	0.11384303	0.0164256
W =	9.87341341	6.71768243	4.12861517	2.01219486	0.28497321
Ws =	6.85844245	5.08354112	3.4090334	1.81404911	0.28039725
L*W*C1 =	19998.2139	9638.54533	3761.24238	916.297474	18.7234234
Ws * C2 + C3 =	11858.4425	10083.5411	8409.0334	6814.04911	5280.39725
Total Cost =	31856.6564	19722.0864	12170.2758	7730.34658	5299.12067

s

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.07259299	0.05525288	0.03791276	0.02057265	0.00323254
L =	0.39705027	0.28012479	0.17805908	0.0896161	0.01309951
W =	9.25723622	6.3733556	3.97219211	1.9677221	0.28391203
Ws =	6.72463248	5.0137069	3.37993429	1.80661323	0.28024147
L*W*C1 =	14702.3525	7141.3397	2829.13947	705.358304	14.8764322
Ws * C2 + C3 =	11724.6325	10013.7069	8379.93429	6806.61323	5280.24147
Total Cost =	26426.9849	17155.0466	11209.0738	7511.97154	5295.1179

4 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.07259299	0.05525288	0.03791276	0.02057265	0.00323254
L =	0.37661593	0.27118632	0.17522761	0.08917729	0.01309787
W =	10.8214466	7.54138418	4.74160277	2.36044948	0.34081509
Ws =	8.14939387	6.06447615	4.07848831	2.17433583	0.33643688
L*W*C1 =	16302.1168	8180.48079	3323.4389	841.993943	17.8558113
Ws * C2 + C3 =	13149.3939	11064.4761	9078.48831	7174.33583	5336.43688
Total Cost =	29451.5107	19244.9569	12401.9272	8016.32977	5354.29269

Table 2: Performance Parameters, Baseline Data, $C_1 = \$4000$, $C_2 = \$1000$, $C_3 = \$5000$

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.72592989	0.55252877	0.37912764	0.20572652	0.03232539
L =	6.6218285	6.18759249	5.35181103	3.29210953	0.23919303
W =	181.056757	97.9776509	40.0255109	8.24163915	0.26697789
Ws =	27.3389617	15.8230296	7.43065468	2.26805994	0.216186
L*W*C1 =	4795707.18	2424983.11	856835.884	108529.515	255.437009
Ws * C2 + C3 =	32338.9617	20823.0296	12430.6547	7268.05994	5216.186
Total Cost =	4828046.14	2445806.14	869266.538	115797.575	5471.623

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.72592989	0.55252877	0.37912764	0.20572652	0.03232539
L =	5.62266398	5.19209172	4.38653896	2.63378366	0.23494537
W =	153.895611	82.5580877	33.5228091	7.38743188	0.30256041
Ws =	27.3555452	15.8624074	7.52939396	2.44554483	0.24800654
L*W*C1 =	3461213.23	1714596.65	588196.432	77827.5896	284.340676
Ws * C2 + C3 =	32355.5452	20862.4074	12529.394	7445.54483	5248.00654
Total Cost =	3493568.77	1735459.06	600725.826	85273.1344	5532.34721

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.72592989	0.55252877	0.37912764	0.20572652	0.03232539
L =	5.61909406	5.17991683	4.33597466	2.4498381	0.19202987
W =	153.437335	81.8998679	32.7138965	6.92279504	0.29307014
Ws =	27.2848256	15.7563007	7.38648295	2.34668085	0.24644318
L*W*C1 =	3448715.27	1696938.02	567386.505	67838.9082	225.112881
Ws * C2 + C3 =	32284.8256	20756.3007	12386.483	7346.68085	5246.44318
Total Cost =	3481000.1	1717694.32	579772.988	75185.589	5471.55606

mary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.72592989	0.55252877	0.37912764	0.20572652	0.03232539
L =	4.62354099	4.1979122	3.42888676	1.95003688	0.18919966
W =	126.924662	67.451439	27.3537815	6.50815417	0.33992805
Ws =	27.3729749	15.9136407	7.65340766	2.63651235	0.28873437
L*W*C1 =	2347365.51	1132620.88	375172.077	50764.5625	257.257079
Ws * C2 + C3 =	32372.9749	20913.6407	12653.4077	7636.51235	5288.73437
Total Cost =	2379738.48	1153534.52	387825.485	58401.0749	5545.99145

4 Primary / 2 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.72592989	0.55252877	0.37912764	0.20572652	0.03232539
L =	4.6066966	4.15457242	3.30883804	1.70972296	0.14814769
W =	125.133785	65.5327464	25.7633384	5.90972997	0.32868526
Ws =	27.0420483	15.5399096	7.31200056	2.48883176	0.28670884
L*W*C1 =	2305813.54	1089042.16	340986.856	40416.004	194.775844
Ws * C2 + C3 =	32042.0483	20539.9096	12312.0006	7488.83176	5286.70884
Total Cost =	2337855.59	1109582.07	353298.856	47904.8358	5481.48468

4 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.72592989	0.55252877	0.37912764	0.20572652	0.03232539
L =	3.62737822	3.21706099	2.52343222	1.37449958	0.14640784
W =	100.884859	53.5242507	22.2372441	5.95285388	0.39314726
Ws =	27.4494972	16.0845534	7.94558418	2.94518729	0.34567754
L*W*C1 =	1463790.16	688763.116	224456.713	32728.7806	230.239371
Ws * C2 + C3 =	32449.4972	21084.5534	12945.5842	7945.18729	5345.67754
Total Cost =	1496239.65	709847.669	237402.297	40673.9679	5575.91691

Table 3: Performance Parameters for λ*10, μ and C_1 = $4000, C_2 = $1000, C_3 = $5000

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.0072593	0.00552529	0.00379128	0.00205727	0.00032325
L =	0.04553666	0.03428758	0.02327697	0.01249784	0.00194329
W =	0.49521733	0.37235253	0.25243071	0.13535166	0.02101808
Ws =	0.47366838	0.36001523	0.24669	0.13368106	0.02097732
L*W*C1 =	90.2021828	51.0682746	23.5032907	6.76641561	0.16337715
Ws * C2 + C3 =	5473.66838	5360.01523	5246.69	5133.68106	5020.97732
Total Cost =	5563.87056	5411.0835	5270.19329	5140.44748	5021.1407

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.0072593	0.00552529	0.00379128	0.00205727	0.00032325
L =	0.04549375	0.03426883	0.02327097	0.01249689	0.00194329
W =	0.56606479	0.42565059	0.28856255	0.15471432	0.02402147
Ws =	0.54177502	0.41169803	0.28204876	0.15281249	0.02397491
L*W*C1 =	103.009648	58.3461913	26.8605191	7.73379315	0.18672264
Ws * C2 + C3 =	5541.77502	5411.69803	5282.04876	5152.81249	5023.97491
Total Cost =	5644.78467	5470.04422	5308.90928	5160.54629	5024.16163

5 Primary / 2 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.0072593	0.00552529	0.00379128	0.00205727	0.00032325
L =	0.03766206	0.02841085	0.01932256	0.01039322	0.00161889
W =	0.56153104	0.42303364	0.28733488	0.15435414	0.02401261
Ws =	0.5411656	0.41135209	0.28188923	0.1527665	0.0239738
L*W*C1 =	84.5936533	48.0749807	22.2081851	6.41694914	0.15549473
Ws * C2 + C3 =	5541.1656	5411.35209	5281.88923	5152.7665	5023.9738
Total Cost =	5625.75925	5459.42707	5304.09741	5159.18345	5024.12929

5 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.0072593	0.00552529	0.00379128	0.00205727	0.00032325
L =	0.03763254	0.02839792	0.01931841	0.01039257	0.00161888
W =	0.65536364	0.49372338	0.33533042	0.18011683	0.02801576
Ws =	0.63192646	0.48023591	0.32902233	0.17827175	0.02797051
L*W*C1 =	98.6520034	56.0828722	25.9122076	7.48750471	0.18141704
Ws * C2 + C3 =	5631.92646	5480.23591	5329.02233	5178.27175	5027.97051
Total Cost =	5730.57847	5536.31879	5354.93454	5185.75925	5028.15193

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.0072593	0.00552529	0.00379128	0.00205727	0.00032325
L =	0.02990482	0.0226004	0.01539857	0.00829734	0.00129469
W =	0.64996987	0.49060919	0.33386911	0.179688	0.02800521
Ws =	0.63110849	0.47977013	0.32880682	0.17820941	0.027969
L*W*C1 =	77.7489252	44.3518601	20.5644316	5.96372625	0.14503224
Ws * C2 + C3 =	5631.10849	5479.77013	5328.80682	5178.20941	5027.969
Total Cost =	5708.85742	5524.12199	5349.37125	5184.17313	5028.11403

4 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.0072593	0.00552529	0.00379128	0.00205727	0.00032325
L =	0.02988611	0.02259219	0.01539593	0.00829692	0.00129469
W =	0.78041666	0.58903257	0.40080309	0.21567803	0.03360767
Ws =	0.75808681	0.57615889	0.39477113	0.21391052	0.03356425
L*W*C1 =	93.2944774	53.2301408	24.6829475	7.15784913	0.17404584
Ws * C2 + C3 =	5758.08681	5576.15889	5394.77113	5213.91052	5033.56425
Total Cost =	5851.38129	5629.38903	5419.45408	5221.06836	5033.73829

Table 4: Performance Parameters for λ, μ*10 and C_1 = $4000, C_2 = $1000, C_3 = $5000

The associated total cost graphs of Table 2 are shown in Figure 6. As expected, as r increases, total cost increases. The low value of r is with no delay for time waiting on service and the high value of r is associated with 36 hours of time waiting on service.

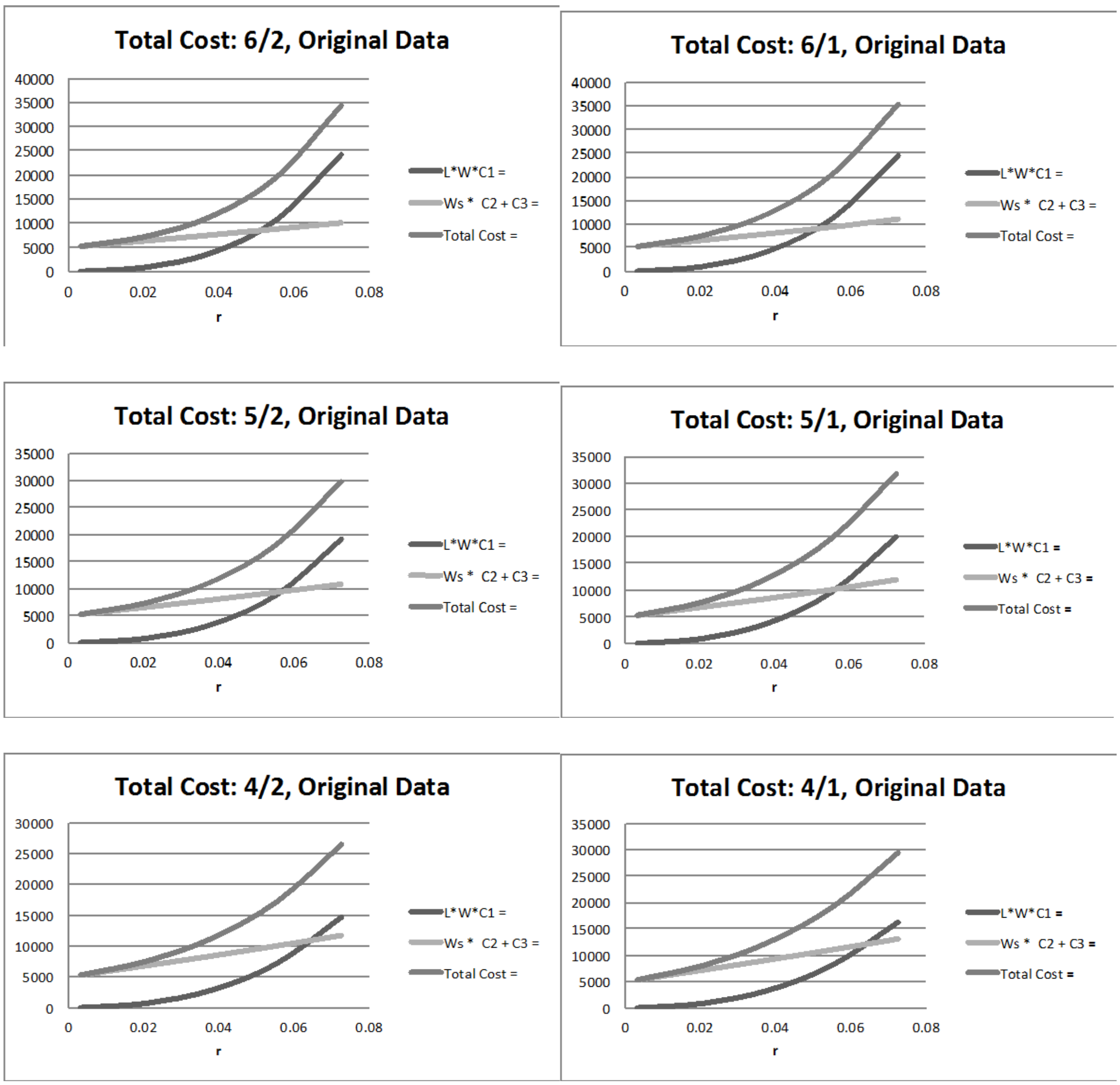

Figure 6: Total Cost for Baseline Data and C_1 = \$4000, C_2 = \$1000, C_3 = \$5000

Figure 7 and Figure 8 show the associated total cost graphs for Table 3 and Table 4 respectively. At the baseline cost, as the arrival rate increases and service rate remains steady, the number of aircraft waiting for service increases and C_1 drives the total cost.

This is reflected in the larger values on the total cost axis compared to the baseline total cost graphs. Also, the cost of maintenance and parts remains fairly flat along the bottom of the graph whereas the cost of lost training function perfectly mirrors the total cost curve.

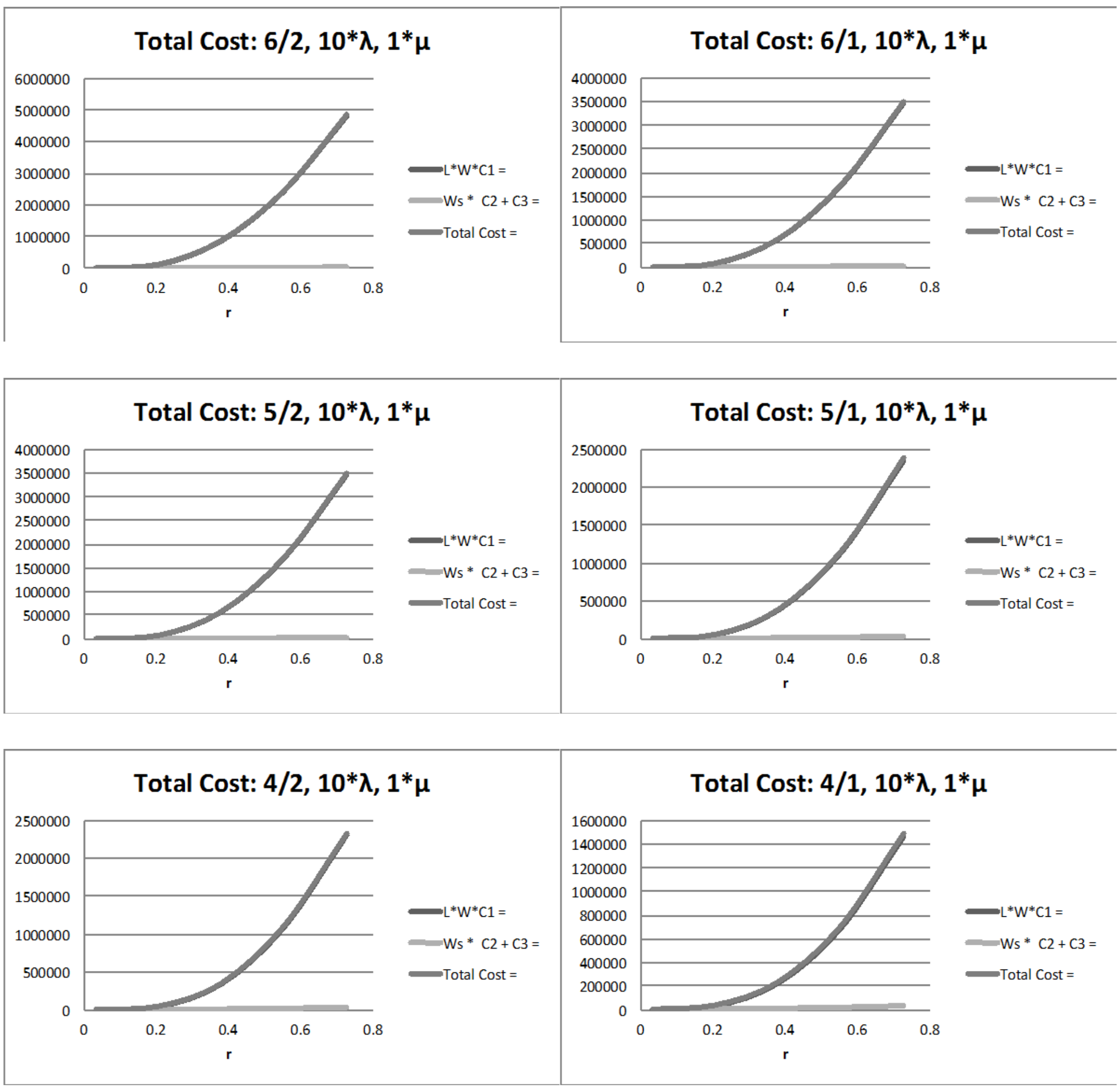

Figure 7: Total Cost for 10*λ, 1*μ, and C_1 = $4000, C_2 = $1000, C_3 = $5000

When the arrival rate is held steady at the baseline level and the service rate is increased, not only do aircraft get through service faster, but a line almost never forms waiting on service. Therefore, the driving cost factor is C_2 and this difference is reflected in the low total cost compared to the baseline data. Also, the cost due to lost training curve remains fairly flat along the bottom of the graph and the cost due to maintenance and parts almost perfectly mirrors the total cost curve.

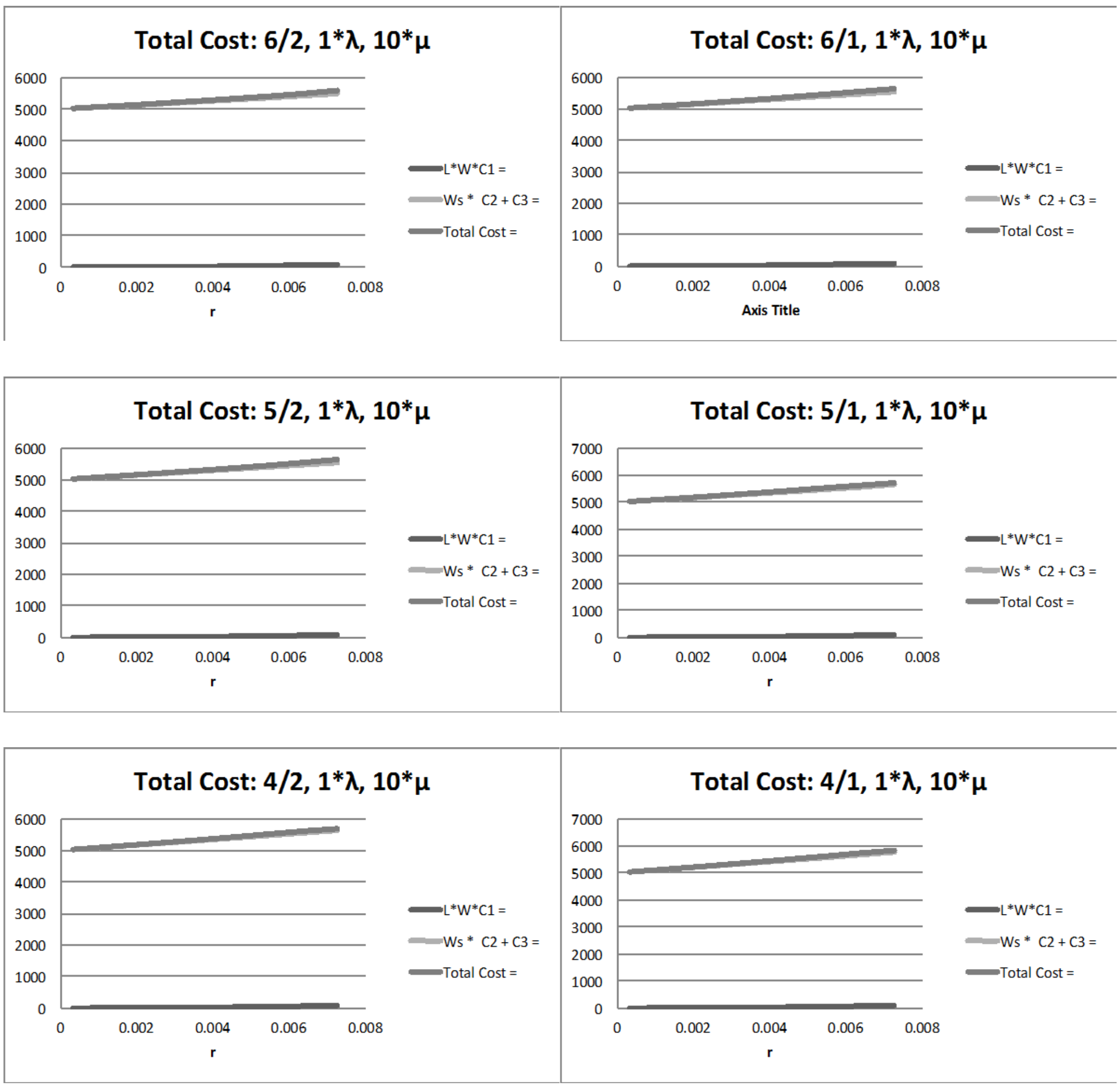

Figure 8: Total Cost for 1*λ, 10*μ, and C_1 = \$4000, C_2 = \$1000, C_3 = \$5000

Varying λ and μ, C_1 and C_3, Delay

In order to show the difference in total cost at the baseline cost level, Figure 9 shows the 6 Primary and 2 Spares model of all three λ and μ combinations side by side.

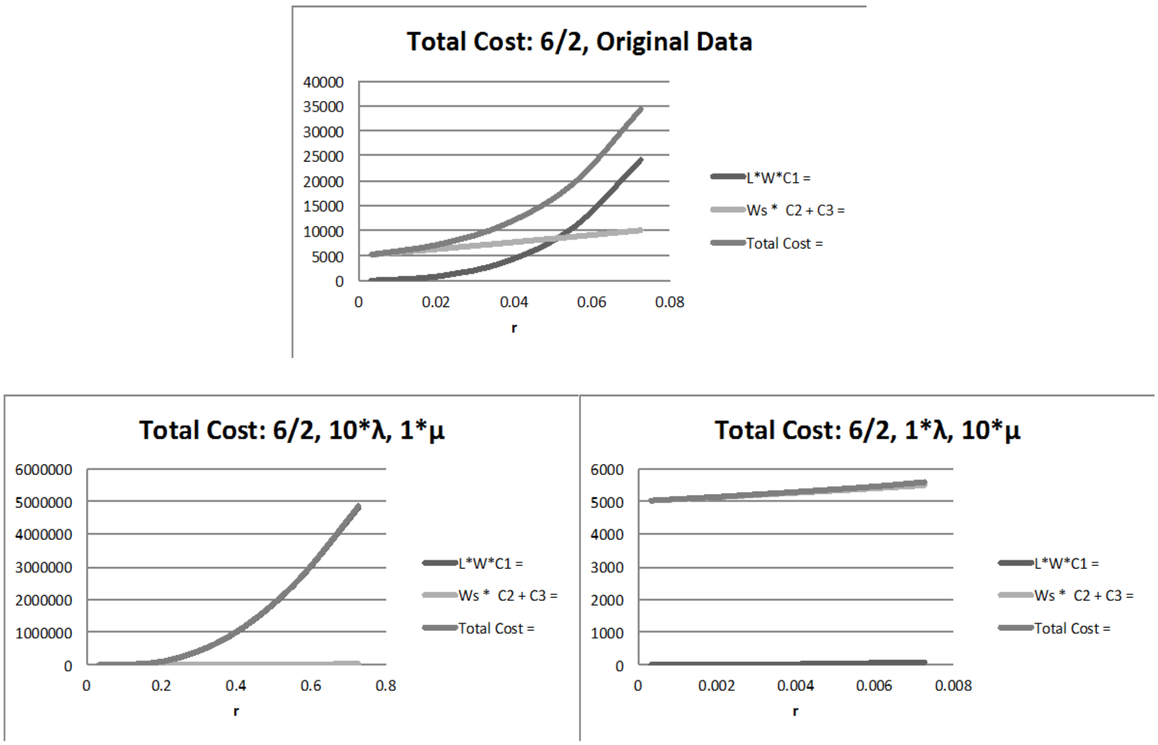

Figure 9: 6 Primary, 2 Spares Model with C_1 = \$4000, C_2 = \$1000, C_3 = \$5000

The vertical or total cost axis clearly shows that as the arrival rate increases, with service rate held steady, the total cost climbs quickly driven by C_1. As the service rate increases, with the arrival rate held steady, the total cost is drastically reduced because C_1 no longer drives the total cost function. Instead C_2 and C_3 drive the cost function. Graphing against all values of C_1 and C_3 while holding C_2 steady for the 6 Primary, 2 Spares model further reinforces this statement. Using the baseline arrival and service rates along with a 36 hour delay results in a total cost that is a function of both parts cost and lost training as shown in Figure 10. Total cost is dominated by the cost of lost training when the arrival rate is increased ten fold while holding a baseline service rate as shown in Figure 11 and total

cost is dominated by the cost of parts when the service rate is increased ten fold while holding a baseline arrival rate as shown in Figure 12.

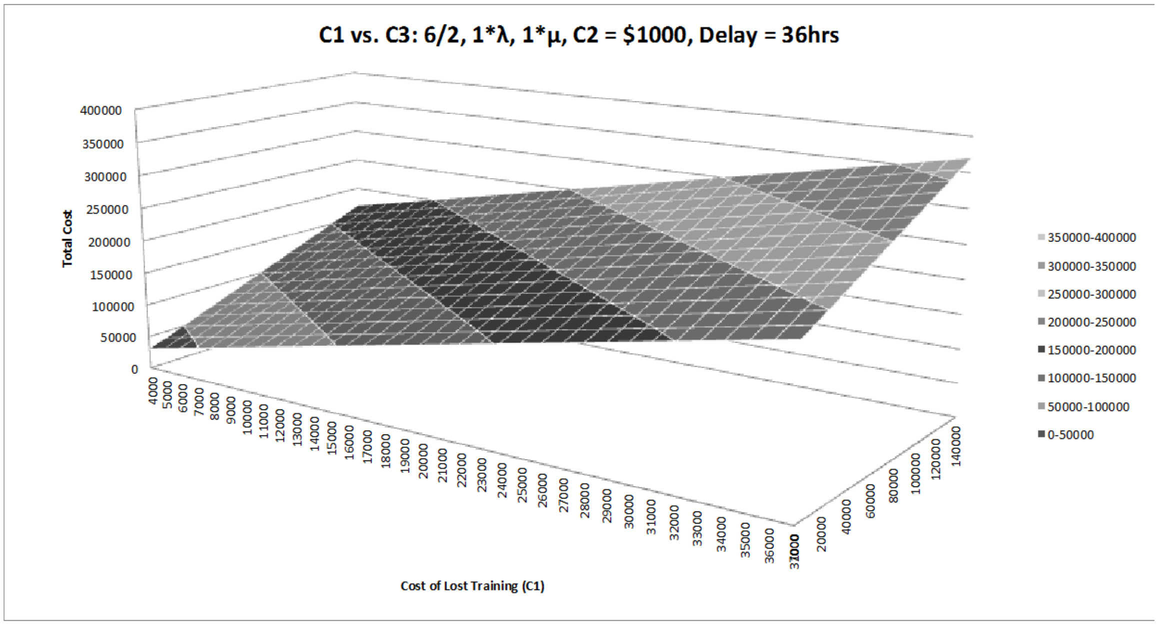

Figure 10: C_1 vs. C_3, 6 Primary, 2 Spares, 1*λ, 1*μ, C_2 = $1000, Delay = 36 hours

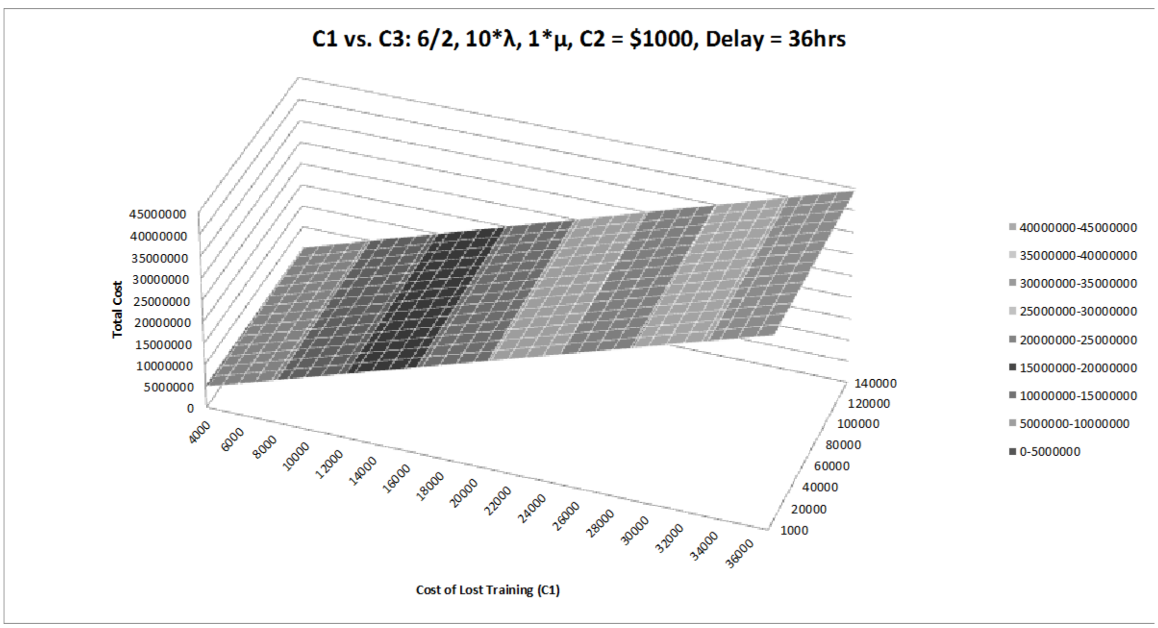

Figure 11: C_1 vs. C_3, 6 Primary, 2 Spares, 10*λ, 1*μ, C_2 = $1000, Delay = 36 hours

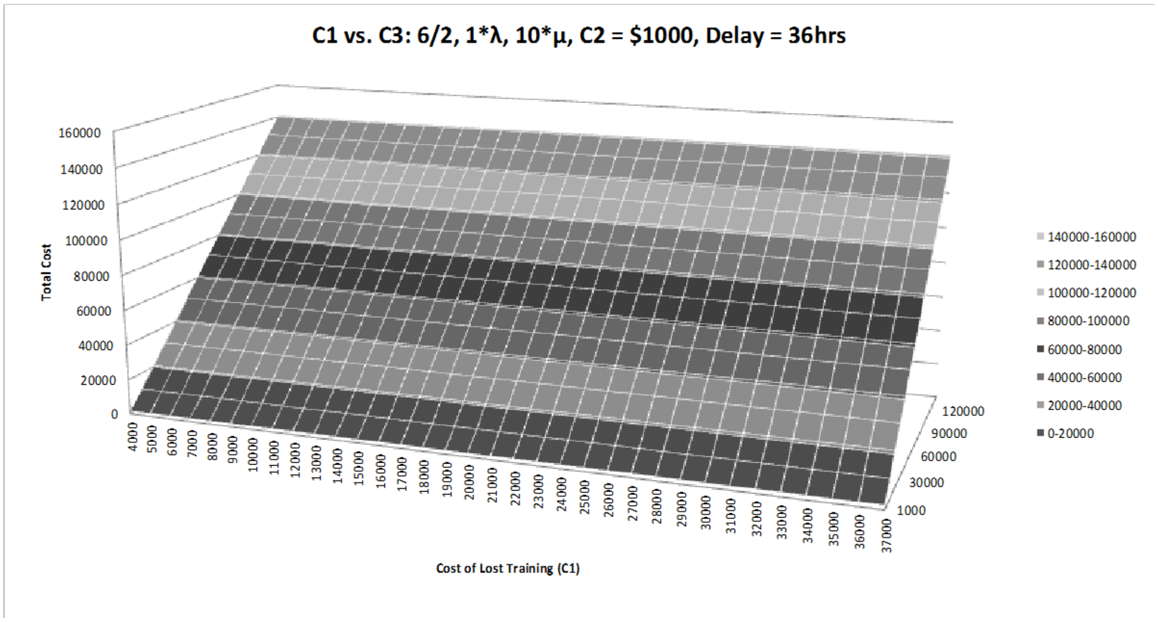

Figure 12: C_1 vs. C_3, 6 Primary, 2 Spares, 1*λ, 10*μ, C_2 = $1000, Delay = 36 hours

When modeled with no waiting time for service the dominating costs in the total cost function changes. Using baseline arrival and service rates with no delay, the average number of aircraft in the system at any given time is 0.0198, the average time in the system is 0.214 hours, and the average time spent in service is 0.21 hours. Therefore, the system is never short and there is no lost training and the cost of parts dominates the total cost function as shown in Figure 13. A ten fold increase in arrival rate while holding a baseline service rate still doesn't make the system short because an aircraft is fixed before the next aircraft enters and the cost of parts still dominates the total cost function as shown in Figure 14. It holds then, that an increase in service rate while holding the baseline arrival rate still won't result in a short system and the cost of parts still dominates the total cost function.

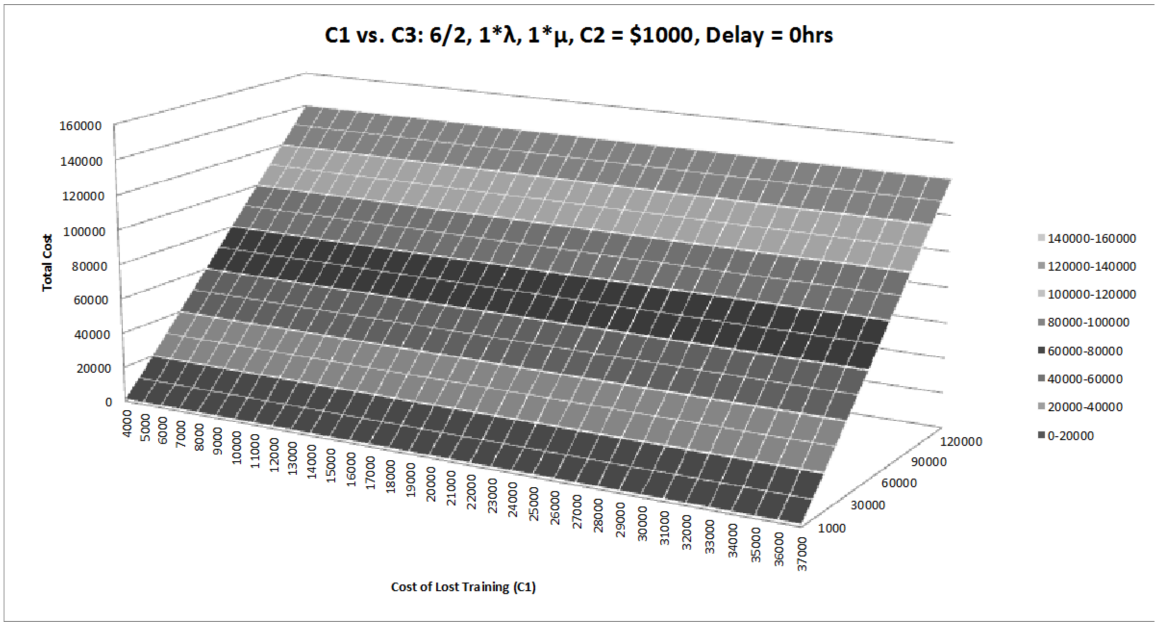

Figure 13: C_1 vs. C_3, 6 Primary, 2 Spares, 1*λ, 1*μ, C_2 = $1000, Delay = 0 hours

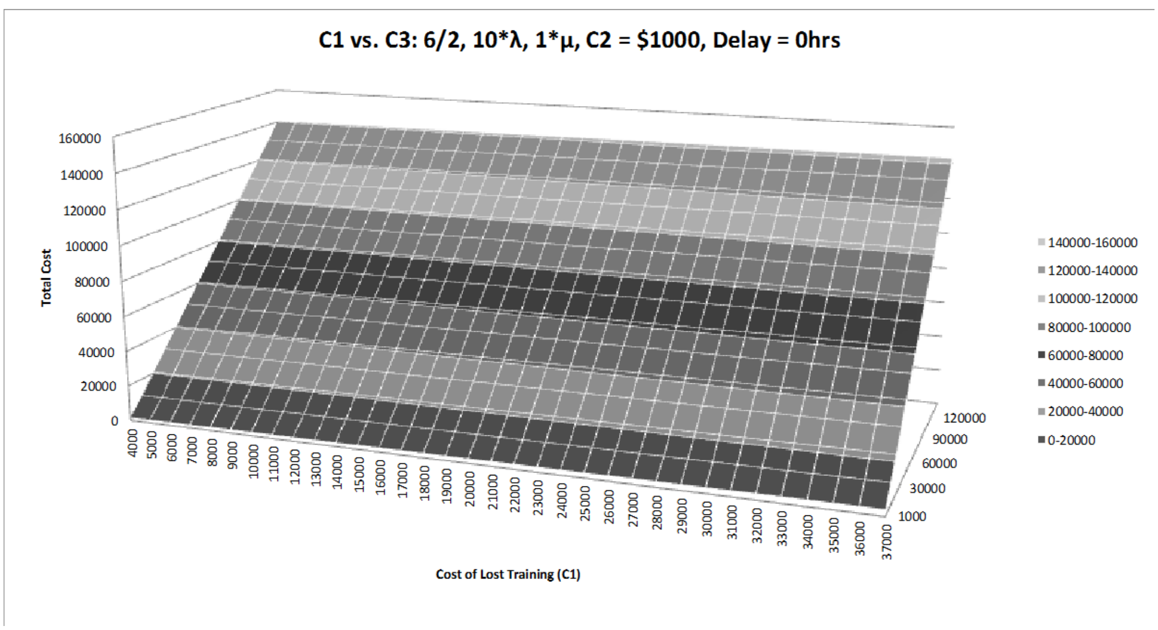

Figure 14: C_1 vs. C_3, 6 Primary, 2 Spares, 10*λ, 1*μ, C_2 = $1000, Delay = 0 hours

Holding C_1, C_2, and C_3 at baseline while ranging λ and μ from baseline to ten fold also provides useful information. In order to accomplish this, λ and μ are modeled from their given value to ten times the given value and with delays of 36, 27, 18, 9, and 0

hours added in. The resulting r (traffic intensity) for the 6 Primary, 1 Spare model and 36 hour delay is shown in Table 5. The graphical depiction is shown in Figure 15.

						μ					
		0.02654084	0.05308169	0.07962253	0.10616337	0.13270422	0.15924506	0.1857859	0.21232675	0.23886759	0.26540843
	0.00192668	0.07259299	0.03629649	0.02419766	0.01814825	0.0145186	0.01209883	0.01037043	0.00907412	0.00806589	0.0072593
	0.00385336	0.14518598	0.07259299	0.04839533	0.03629649	0.0290372	0.02419766	0.02074085	0.01814825	0.01613178	0.0145186
	0.00578004	0.21777897	0.10888948	0.07259299	0.05444474	0.04355579	0.03629649	0.03111128	0.02722237	0.02419766	0.0217779
	0.00770672	0.29037196	0.14518598	0.09679065	0.07259299	0.05807439	0.04839533	0.04148171	0.03629649	0.03226355	0.0290372
λ	0.0096334	0.36296495	0.18148247	0.12098832	0.09074124	0.07259299	0.06049416	0.05185214	0.04537062	0.04032944	0.03629649
	0.01156007	0.43555793	0.21777897	0.14518598	0.10888948	0.08711159	0.07259299	0.06222256	0.05444474	0.04839533	0.04355579
	0.01348675	0.50815092	0.25407546	0.16938364	0.12703773	0.10163018	0.08469182	0.07259299	0.06351887	0.05646121	0.05081509
	0.01541343	0.58074391	0.29037196	0.1935813	0.14518598	0.11614878	0.09679065	0.08296342	0.07259299	0.0645271	0.05807439
	0.01734011	0.6533369	0.32666845	0.21777897	0.16333423	0.13066738	0.10888948	0.09333384	0.08166711	0.07259299	0.06533369
	0.01926679	0.72592989	0.36296495	0.24197663	0.18148247	0.14518598	0.12098832	0.10370427	0.09074124	0.08065888	0.07259299

Table 5: r values for 6 Primary, 1 Spare Model with 36 hour delay

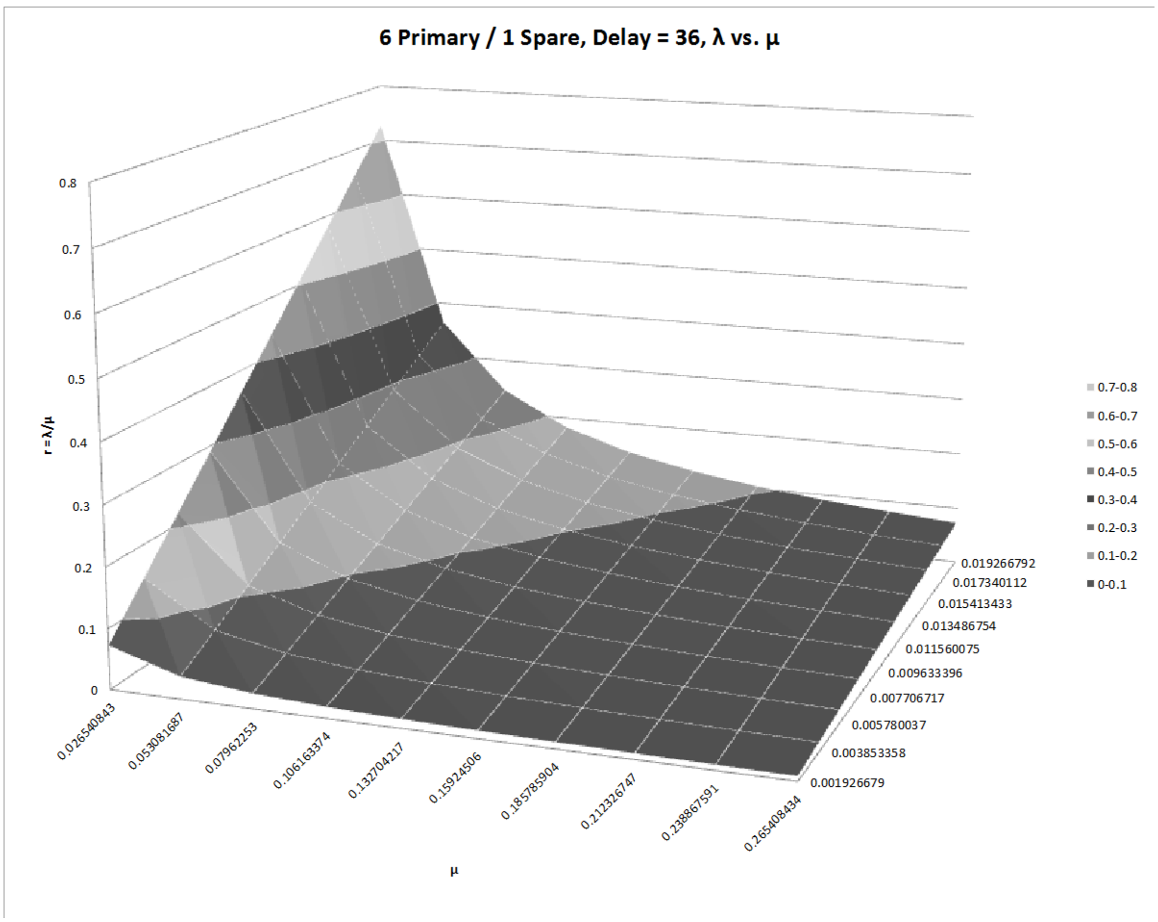

Figure 15: r values for 6 Primary, 1 Spare Model with 36 hour delay

The corresponding total cost graph for the 6 Primary, 1 Spare Model with 36 hour delay is shown in Figure 16. As the traffic intensity increases, the corresponding portion in the total cost graph also increases. Furthermore, as the arrival rate increases, the total cost

increases and as the service rate decreases, the total cost increases. Either of these combinations results in a higher traffic intensity and therefore a higher total cost.

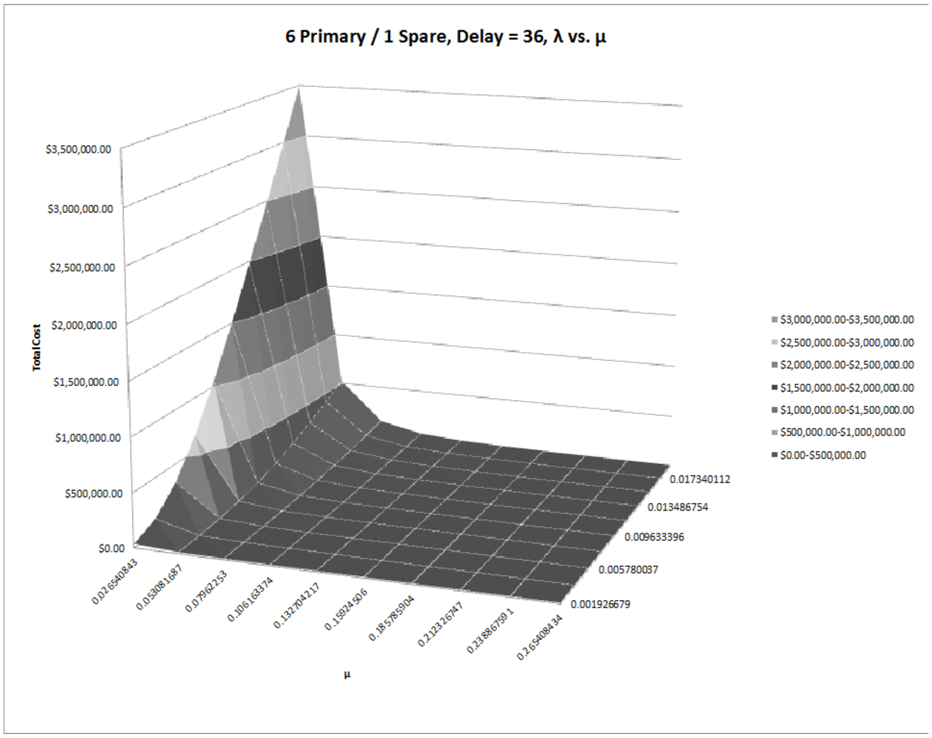

Figure 16: λ vs. μ Total Cost for 6 Primary, 1 Spare Model with 36 hour delay

The total cost graphs for the 6 Primary, 1 Spare Model with delays of 27, 18, 9, and 0 hours follow:

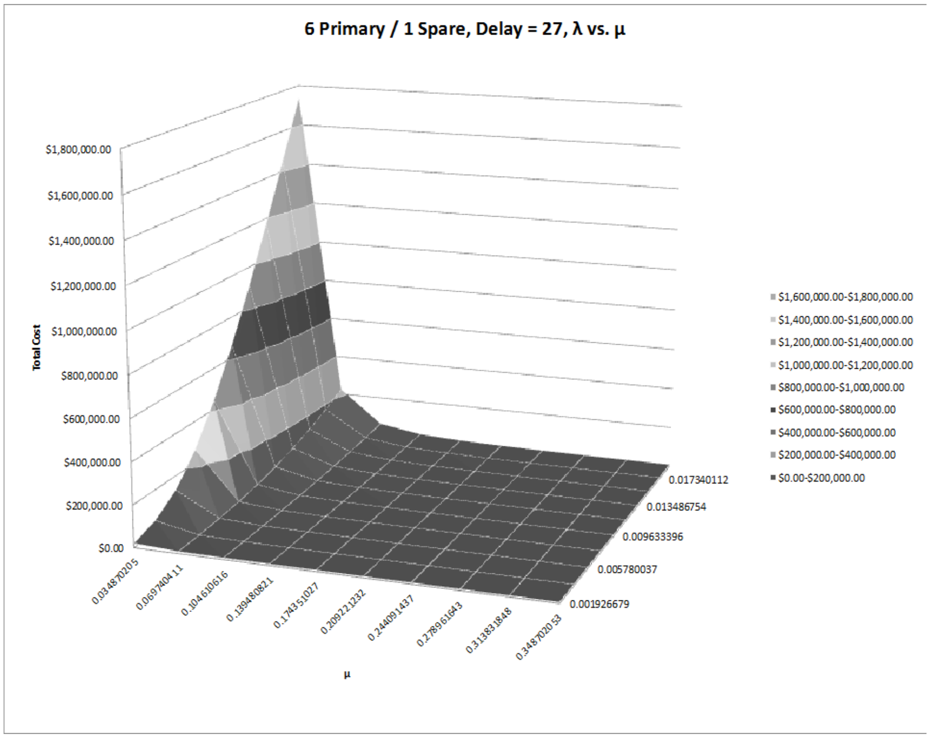

Figure 17: λ vs. μ Total Cost for 6 Primary, 1 Spare Model with 27 hour delay

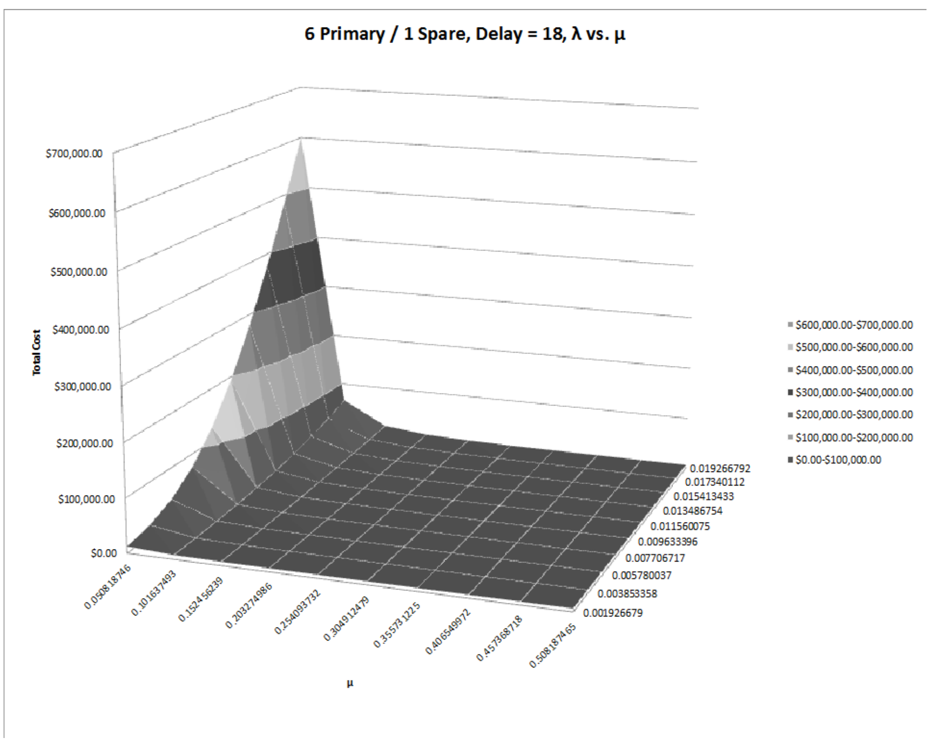

Figure 18: λ vs. μ Total Cost for 6 Primary, 1 Spare Model with 18 hour delay

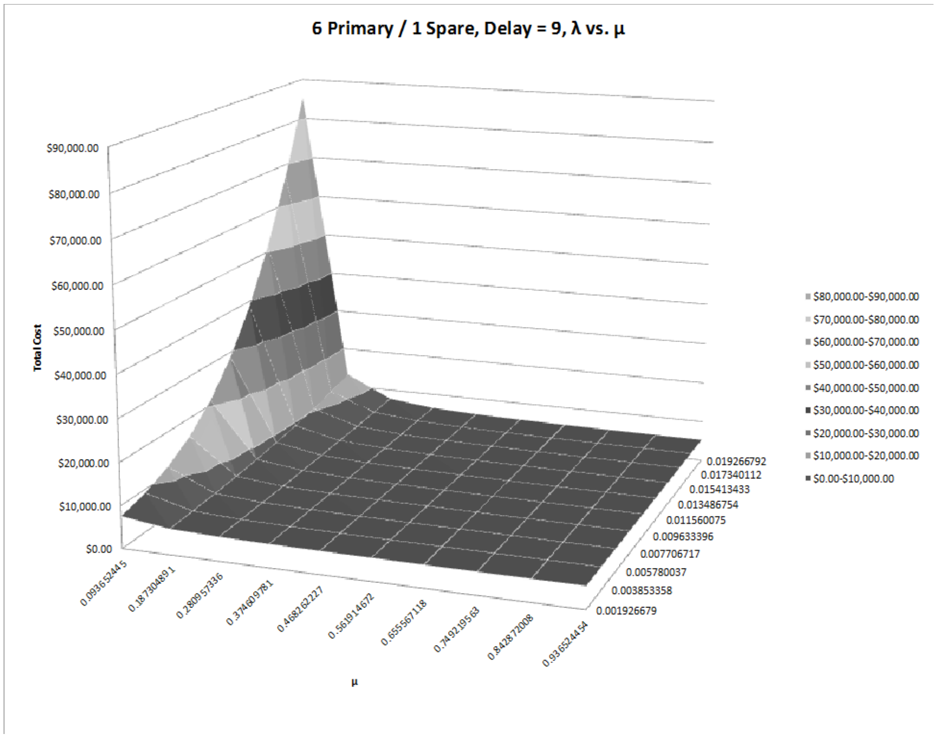

Figure 19: λ vs. μ Total Cost for 6 Primary, 1 Spare Model with 9 hour delay

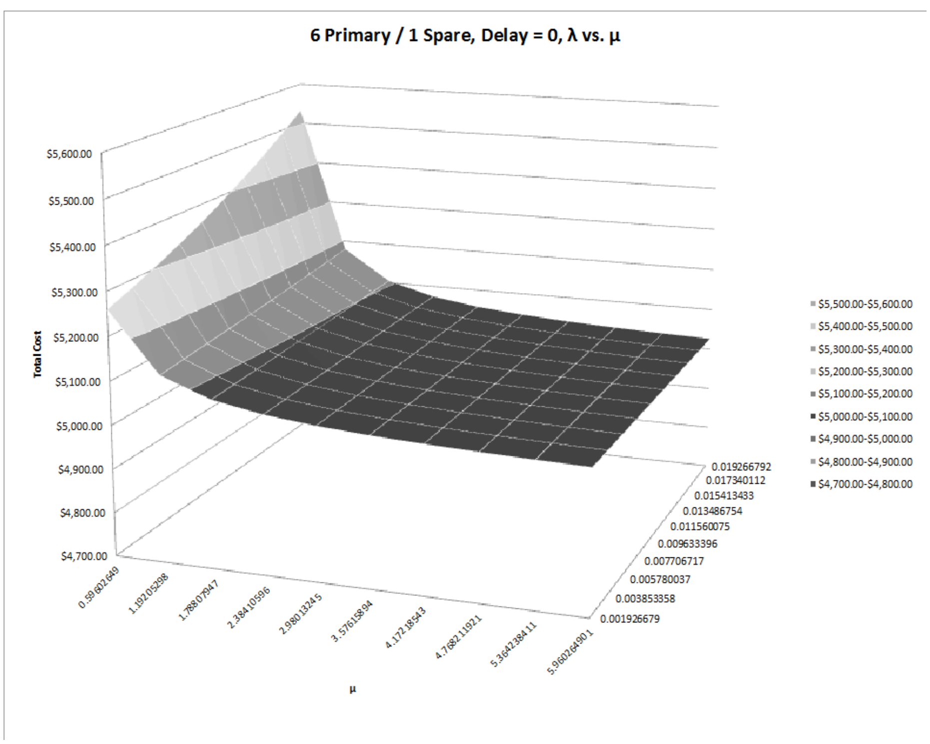

Figure 20: λ vs. μ Total Cost for 6 Primary, 1 Spare Model with 0 hour delay

For this particular NMC driver, the associated total cost is primarily driven by the arrival rate. Across all modeled delays, an increase in service rate eventually negates the cost of lost training and the resultant total cost is purely a result of the cost of maintenance and the cost of parts.

Varying Model

So far, this analysis has looked at varying λ and μ, varying C_1 and C_3, and delay times. However, the model also has an effect on the total cost. Observing the baseline arrival and service rates and costs, as delay increases, the 6 Primary, 1 Spare Model has the highest total cost and all single spare models have a higher cost than their associated 2 spare models (see Figure 21). This is because the 2 spare models negate more lost training than their associated 1 spare model. With 2 spares, the system is short less and therefore loses less training. When the arrival rate is increased ten fold, all 2 spare models have a higher total cost than the 1 spare models because there are just more airplanes to break (see Figure 22).

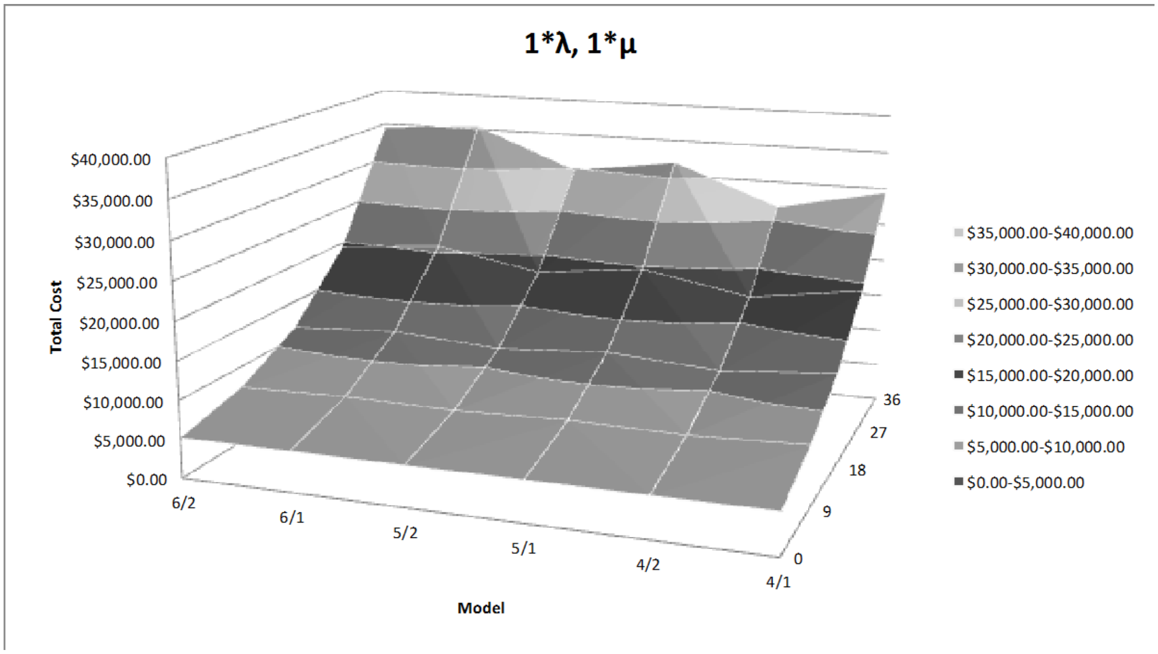

Figure 21: Model vs. Delay, 1*λ, 1*μ, C_1 = $4000, C_2 = $1000, C_3 = $5000

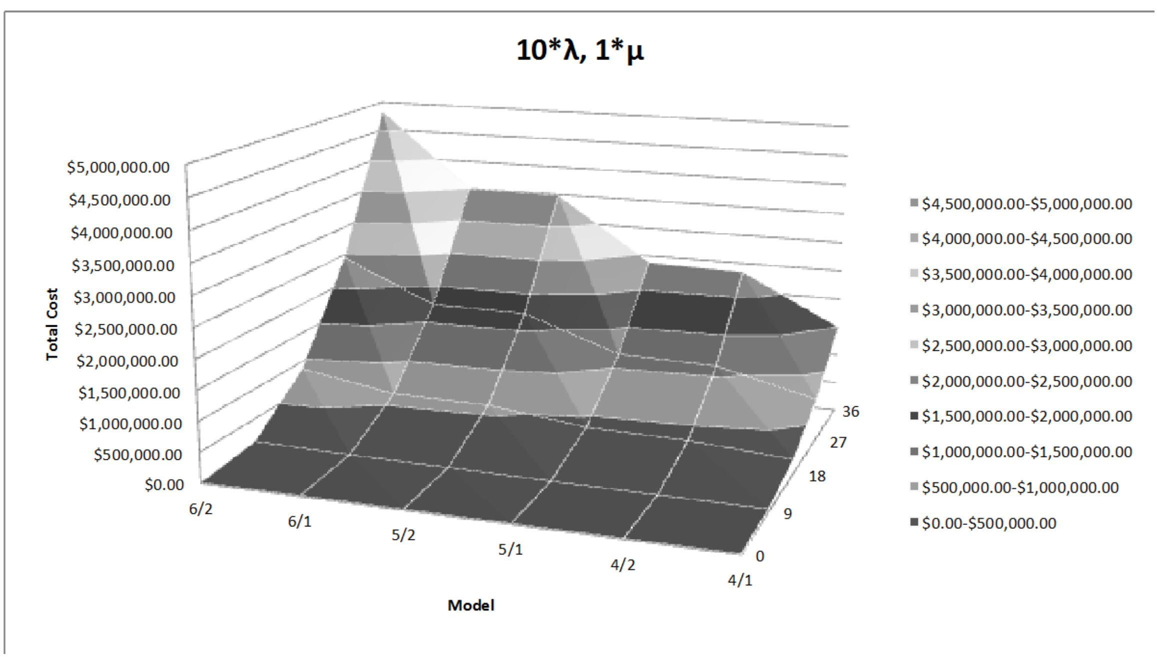

Figure 22: Model vs. Delay, 10*λ, 1*μ, C_1 = $4000, C_2 = $1000, C_3 = $5000

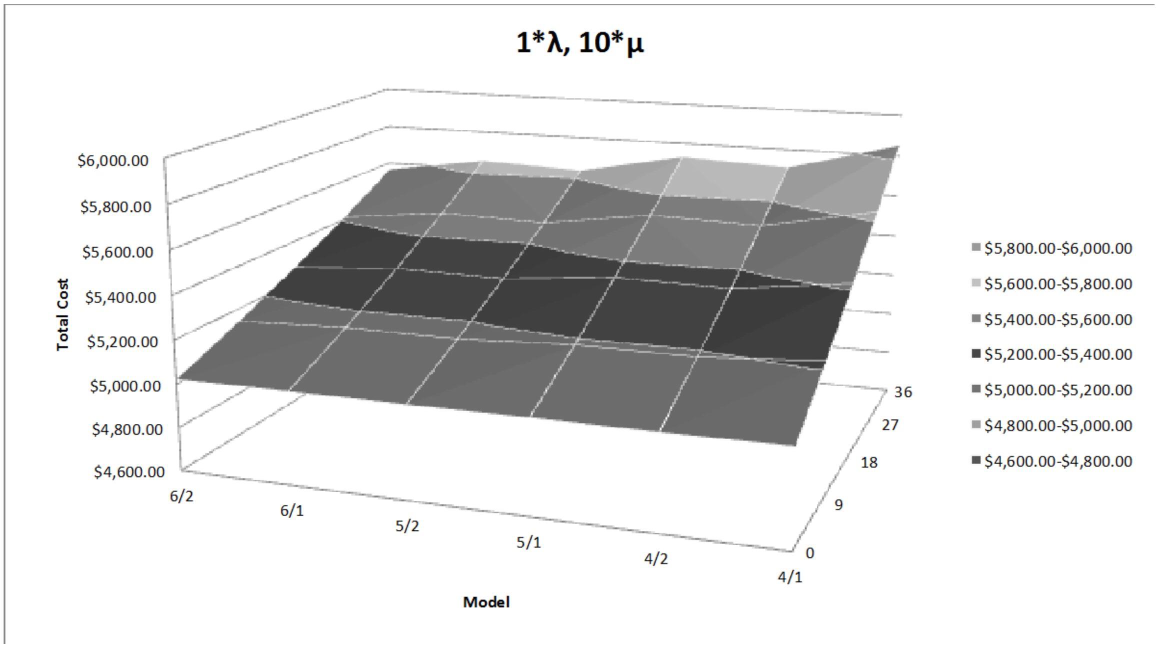

Figure 23: Model vs. Delay, 1*λ, 10*μ, C_1 = \$4000, C_2 = \$1000, C_3 = \$5000

Finally, when service rate is increased ten fold, the 1 spare models are more expensive than their associated 2 spares model with the 4 Primary, 1 Spare model leading the cost competition (see Figure 23).

Cost Comparison

Holding the cost of lost training value to its baseline of $4000/hour and raising the cost of parts to its high limit of $140,000 also has an effect on the dominating costs of the total cost function. At the baseline arrival and service rates the cost of parts now completely dominates the total cost function over all r. An increased arrival rate still keeps the cost of lost training as the dominating factor in the total cost function and an increased service rate still keeps the cost of maintenance and parts as the dominating factor in the total cost function (see Figure 24).

C_3 = \$140,000 C_3 = \$5,000

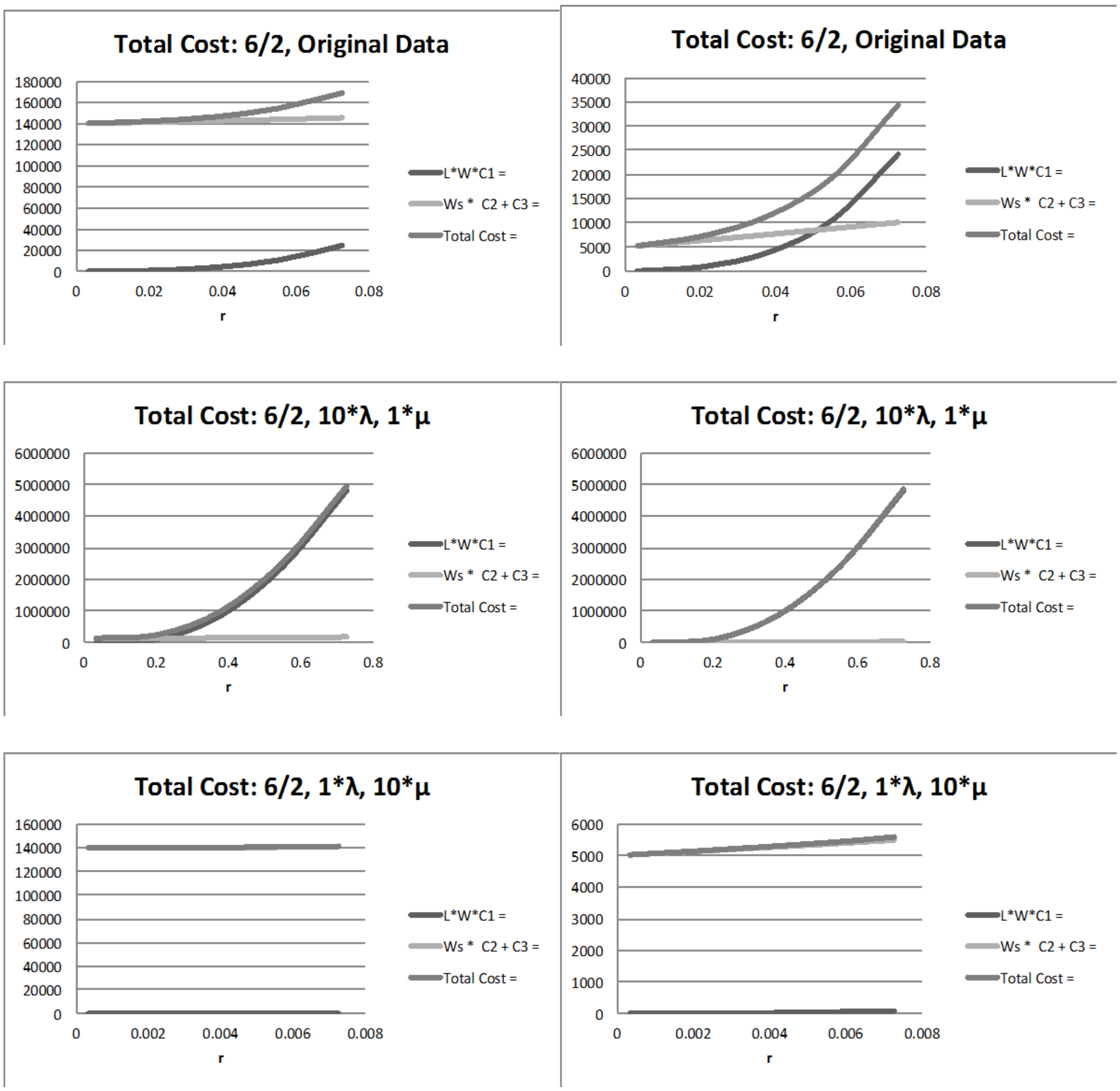

Figure 24: C_3 = \$140,000 vs \$5000 with C_1 = \$4000 and C_2 = \$1000

If, on the other hand, the cost of parts is kept at its baseline of \$5000 and the cost of lost training is raised to its high of \$37,000 per hour, the dominating costs of the total cost function change again. Against the baseline arrival and service rates, the cost of lost training dominates the total cost function over the entire r. At increased arrival rates, the

cost of lost training remains the dominating cost and at increased service rates, the cost of maintenance and parts remains the dominating cost (see Figure 25).

C_1 = \$37,000/hr C_1 = \$4,000/hr

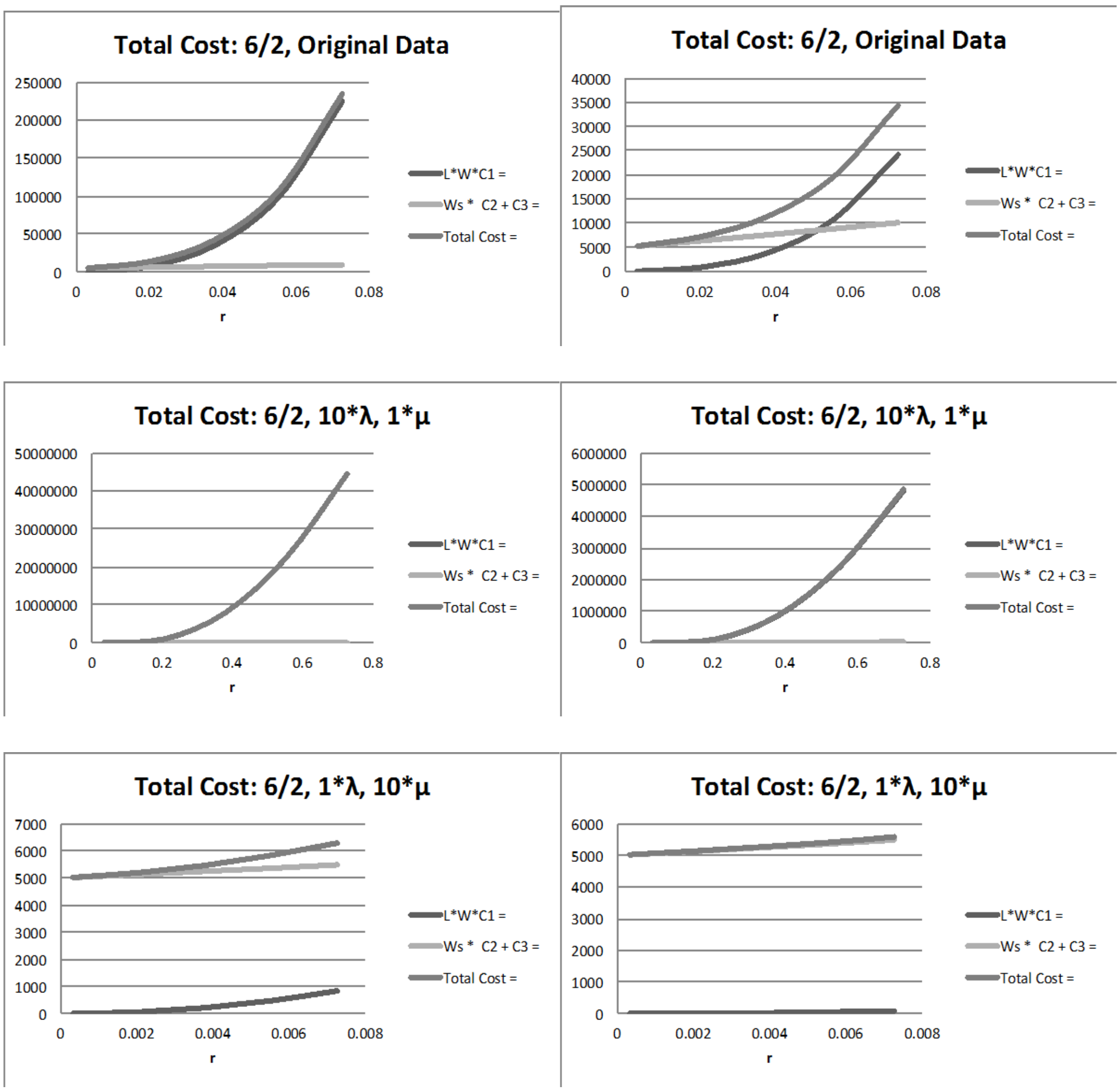

Figure 25: C_1 = \$37,000 vs \$4000 with C_2 = \$1000 and C_3 = \$5000

Figure 24 and Figure 25 provide good information regarding the dominating cost factors across the range of arrival and service rates, but they don't readily show how the total costs compare. Figure 26, Figure 27, and Figure 28 show how the total cost is

affected by alternating the extremes of cost of lost training and cost of parts while keeping the arrival and service rates at the baseline. In this situation, an aircraft that

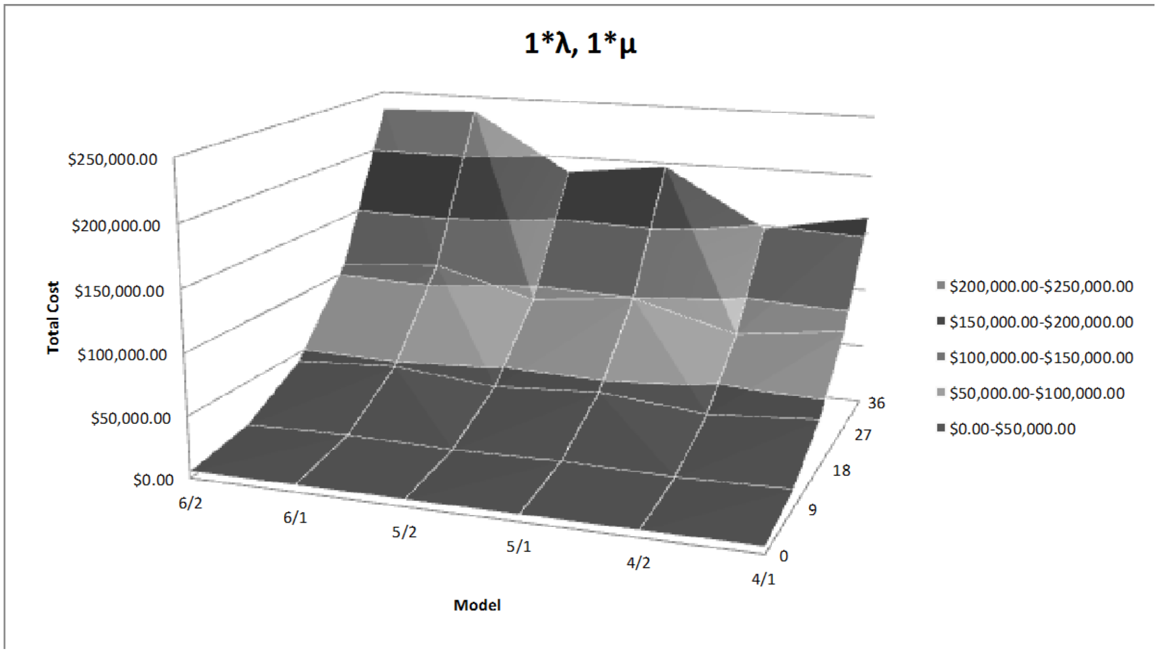

Figure 26: Total Cost by Model with C_1 = \$37,000, C_2 = \$1,000, C_3 = \$5000

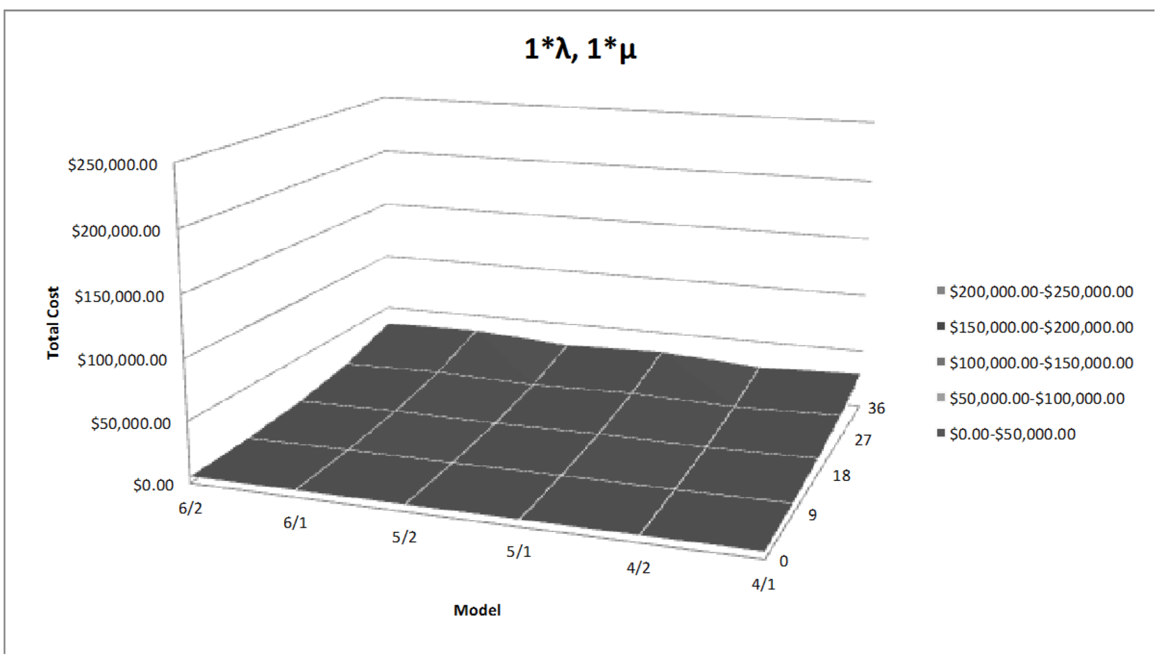

Figure 27: Total Cost by Model with C_1 = \$4,000, C_2 = \$1,000, C_3 = \$5000

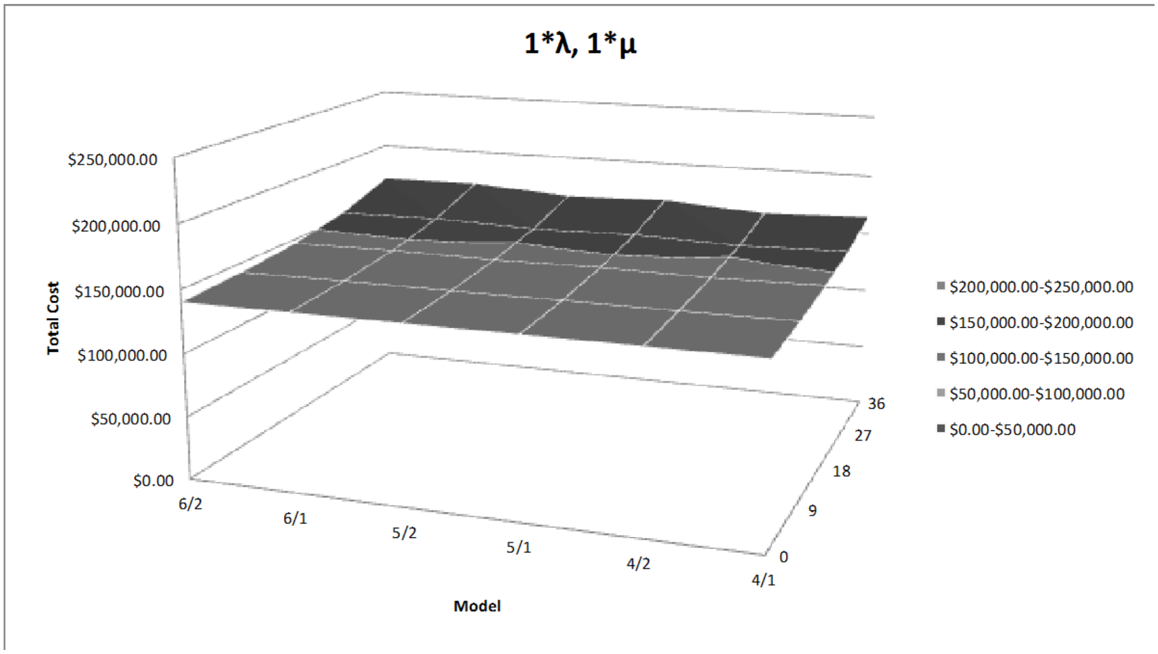

Figure 28: Total Cost by Model with C_1 = $4,000, C_2 = $1,000, C_3 = $140,000

enters service with no delay only has the cost of maintenance and the parts cost in the total cost function. Regardless of the delay or time in service, the cost of parts always provides the floor of the total cost. However a comparison between an expensive part/low cost of lost training and a less expensive part/high cost of lost training should be made. At some delay, the less expensive part/high cost of lost training combination becomes more expensive than the expensive part/low cost of lost training combination. Figure 28 shows a total cost of $150,000 around the 22-hour delay point and tops out around $175,000 while Figure 26 shows a total cost of $150,000 around the 33-hour delay point yet tops out at $240,000. Therefore, at shorter delays, high cost parts drive the total cost and at longer delays, high cost of lost training drives the total cost.

Looking at the same comparison between models and delays with a ten fold increase in arrival rate and the baseline service rate provides Figure 29, Figure 30, and Figure 31.

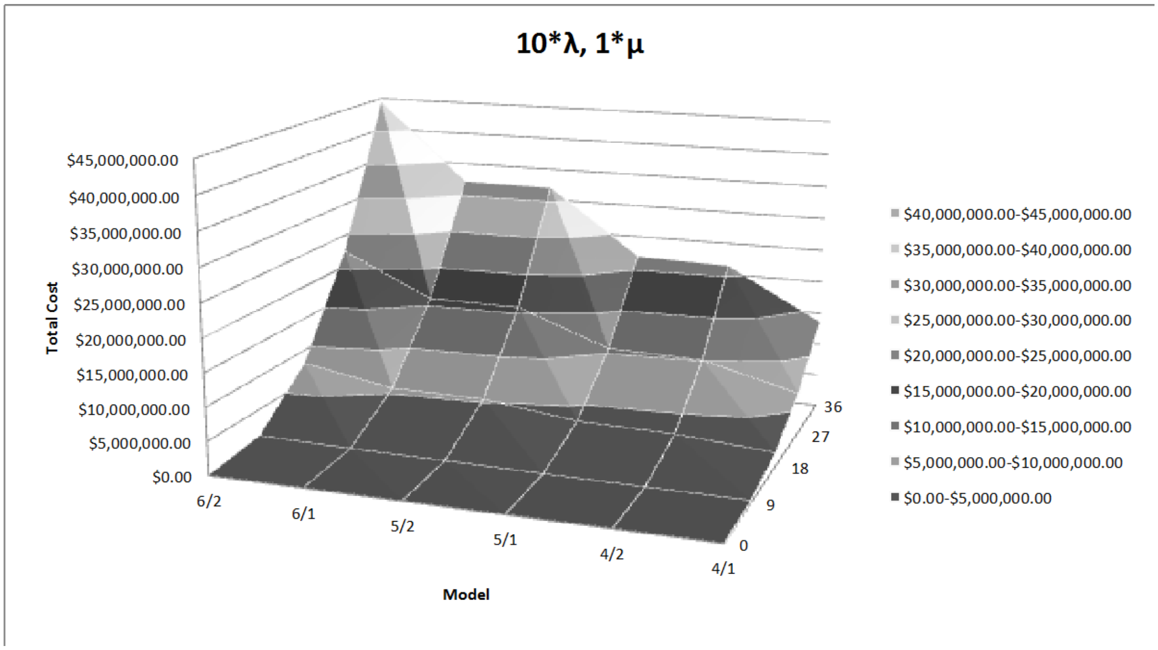

Figure 29: Total Cost by Model with C_1 = \$37,000, C_2 = \$1,000, C_3 = \$5,000

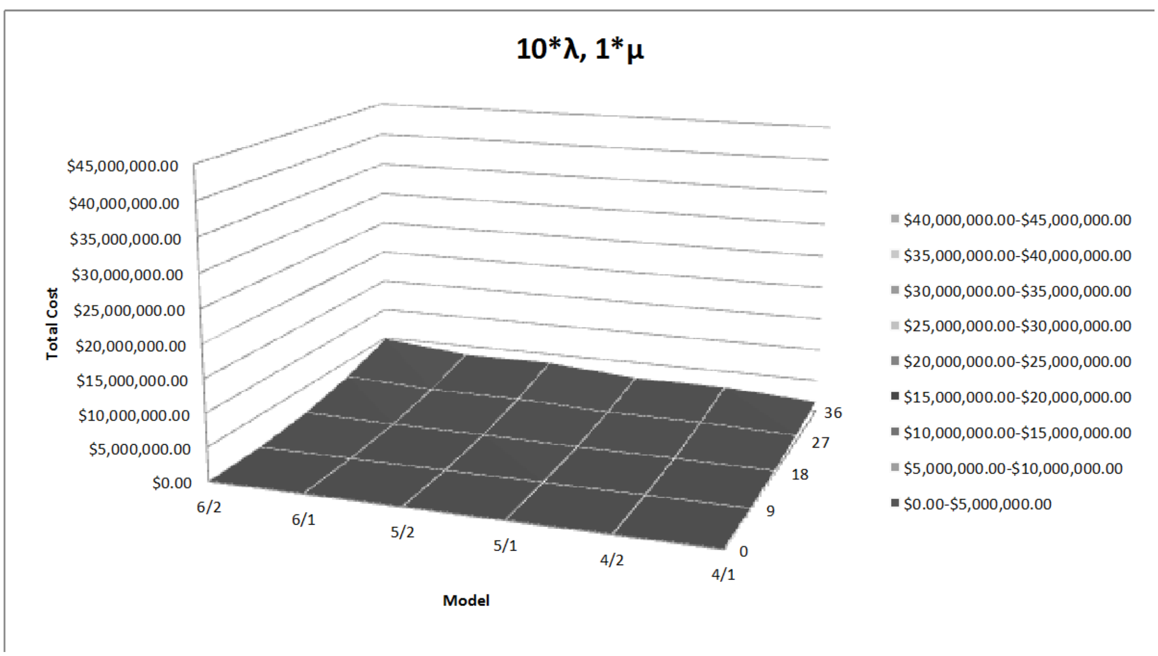

Figure 30: Total Cost by Model with C_1 = \$4,000, C_2 = \$1,000, C_3 = \$5,000

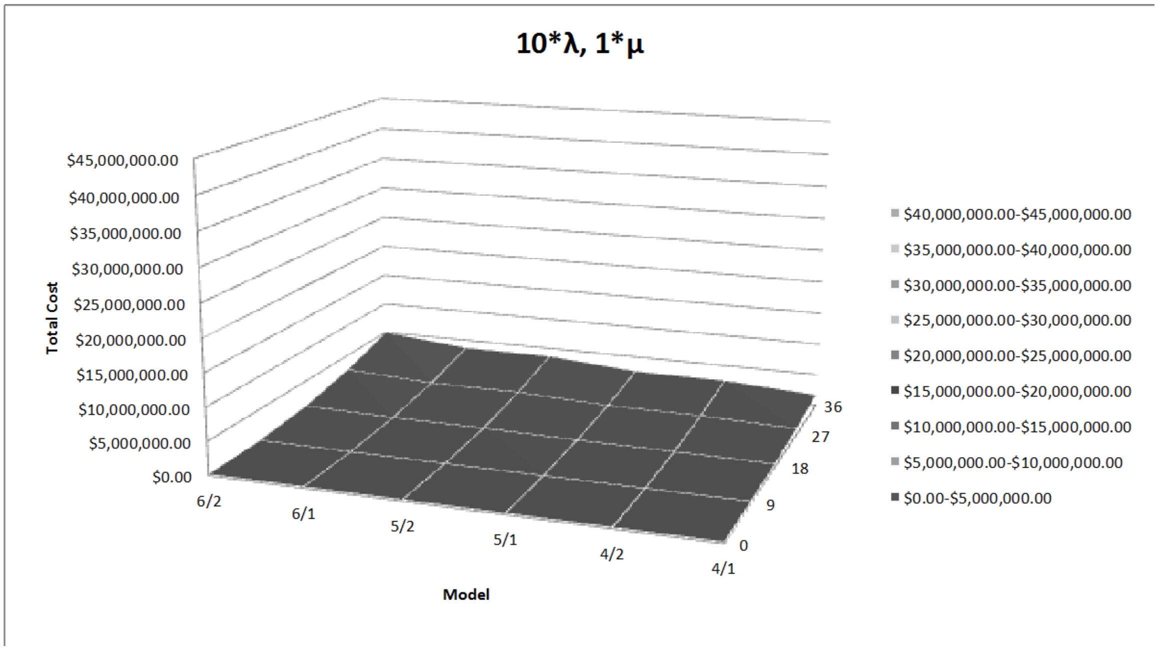

Figure 31: Total Cost by Model with C_1 = $4,000, C_2 = $1,000, C_3 = $140,000

As with the baseline arrival and service rates, the cost of parts always provides the floor of the total cost. However a comparison between an expensive part/low cost of lost training and a less expensive part/high cost of lost training should be made. At some delay, the less expensive part/high cost of lost training combination becomes more expensive than the expensive part/low cost of lost training combination. Figure 31 shows a total cost of $5,000,000 at the 36-hour delay point and tops out at $5,000,000 while Figure 29 shows a total cost of $5,000,000 around the 18-hour delay point yet tops out at $45,000,000. Therefore, at increased arrival rates, the entire range of the cost of lost training dominates the total cost function.

Looking at the same comparison between models and delays with a ten fold increase in service rate and the baseline arrival rate provides Figure 32, Figure 33, and Figure 34.

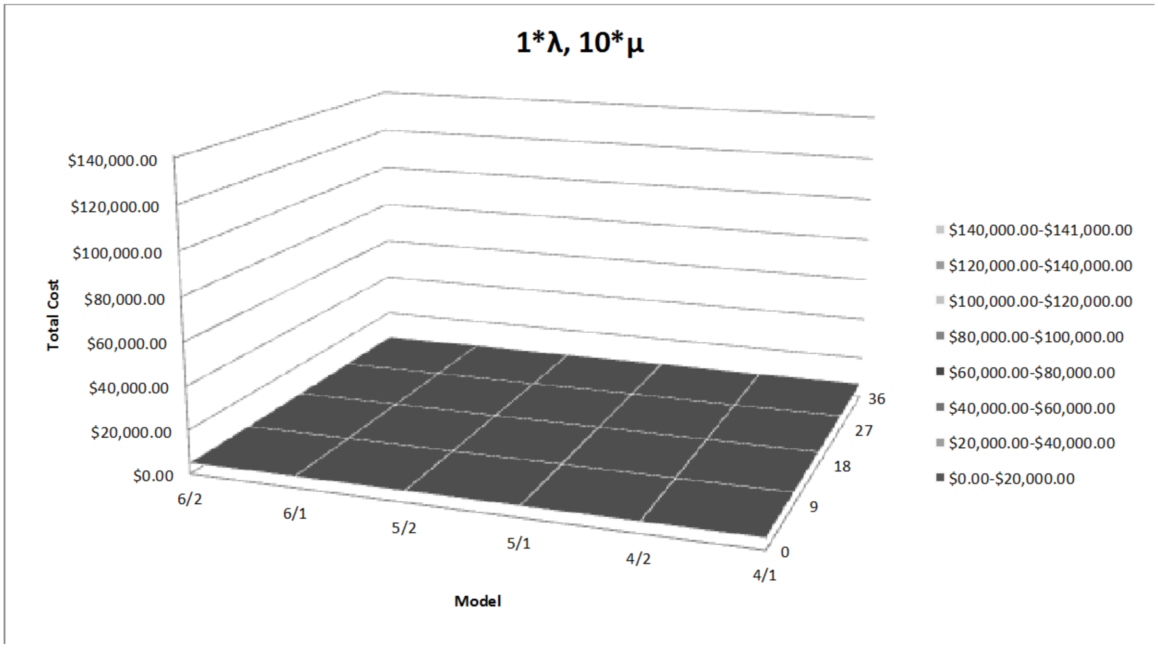

Figure 32: Total Cost by Model with C1 = $37,000, C2 = $1,000, C3 = $5,000

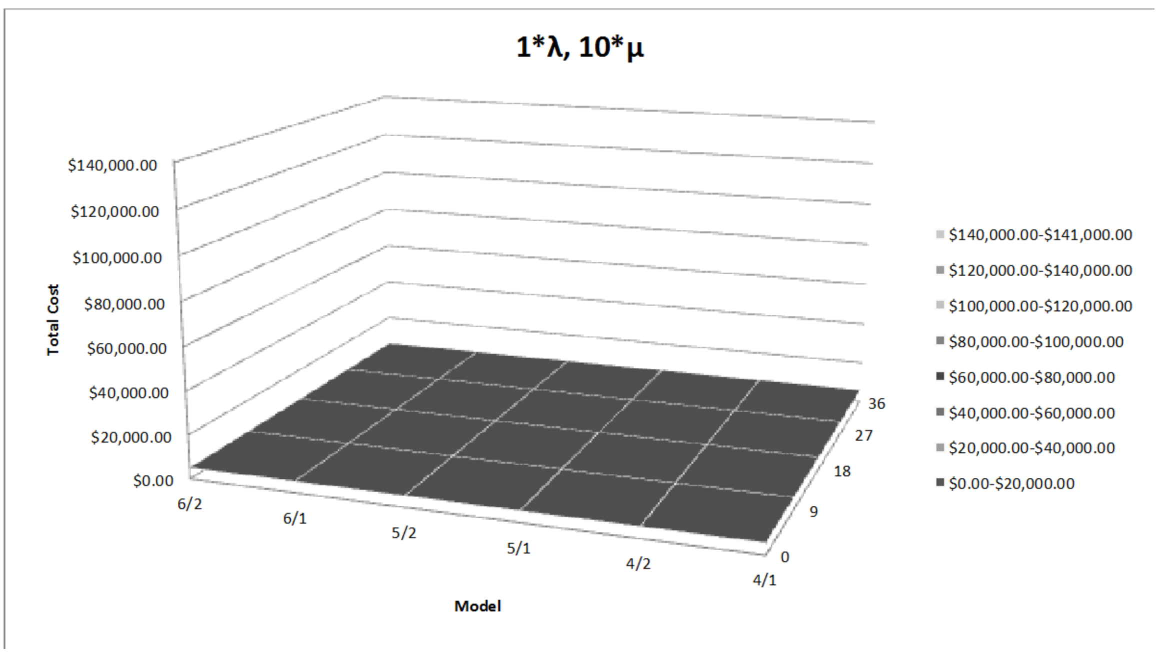

Figure 33: Total Cost by Model with C1 = $4,000, C2 = $1,000, C3 = $5,000

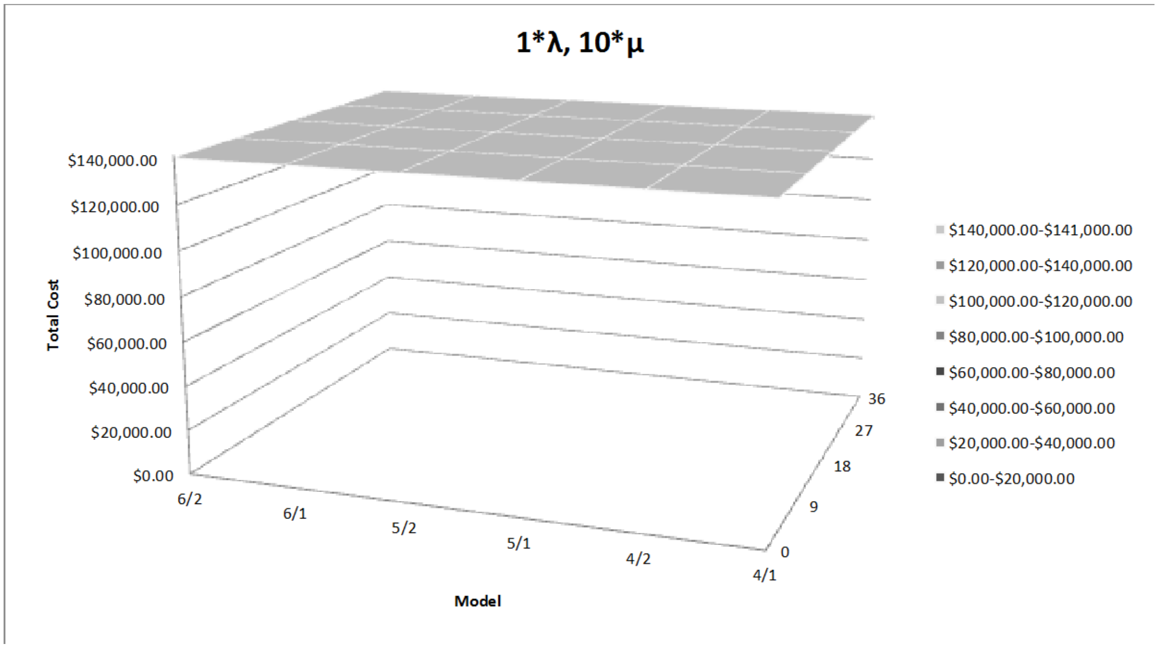

Figure 34: Total Cost by Model with C1 = $4,000, C2 = $1,000, C3 = $140,000

As with the baseline arrival and service rates, the cost of parts always provides the floor of the total cost. However a comparison between an expensive part/low cost of lost training and a less expensive part/high cost of lost training should be made. Unlike the other two comparisons, at no point does the less expensive part/high cost of lost training combination become more expensive than the expensive part/low cost of lost training combination. Figure 34 shows a total cost of $140,000 across all delays while Figure 32 shows a total cost of $5,000 across all delays. Therefore, at increased service rates, the cost of parts and maintenance drives the entire total cost function.

Traffic Intensity (r)

As shown by the last couple figures, it is clear that the traffic intensity or r provides a useful value to determine which cost dominates the total cost function. For small r values, expensive parts drive the cost function and for large r values, the cost of lost training drives the cost function regardless of the determined value of lost training.

However, there is some r value between the low and high values where the cost of lost training, cost of maintenance, and cost of parts all drive the total cost depending on actual costs associated with C_1, C_2, and C_3. Comparing the high cost of lost training/less expensive parts cost to the low cost of lost training/high parts cost combinations provides an r value of approximately 0.11 for the 6 Primary / 2 Spares Model (see Figure 35) and comparing a low cost of lost training/low parts cost to the lowest cost of lost training/high parts cost provides an r value of approximately 0.20 (see Figure 36). Therefore, for the 6 Primary / 2 Spares Model, the cost of parts dominates the total cost for r values less than 0.11 and the cost of lost training dominates the total cost for r values greater than 0.20.

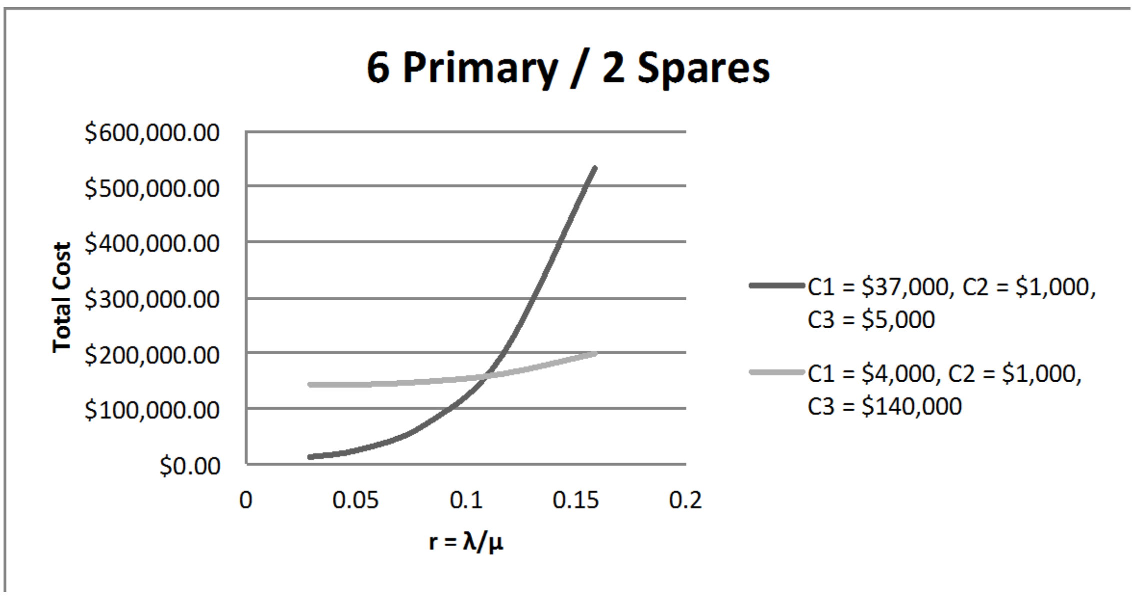

Figure 35: 6 Primary / 2 Spares, Cost of Parts Dominated r Region

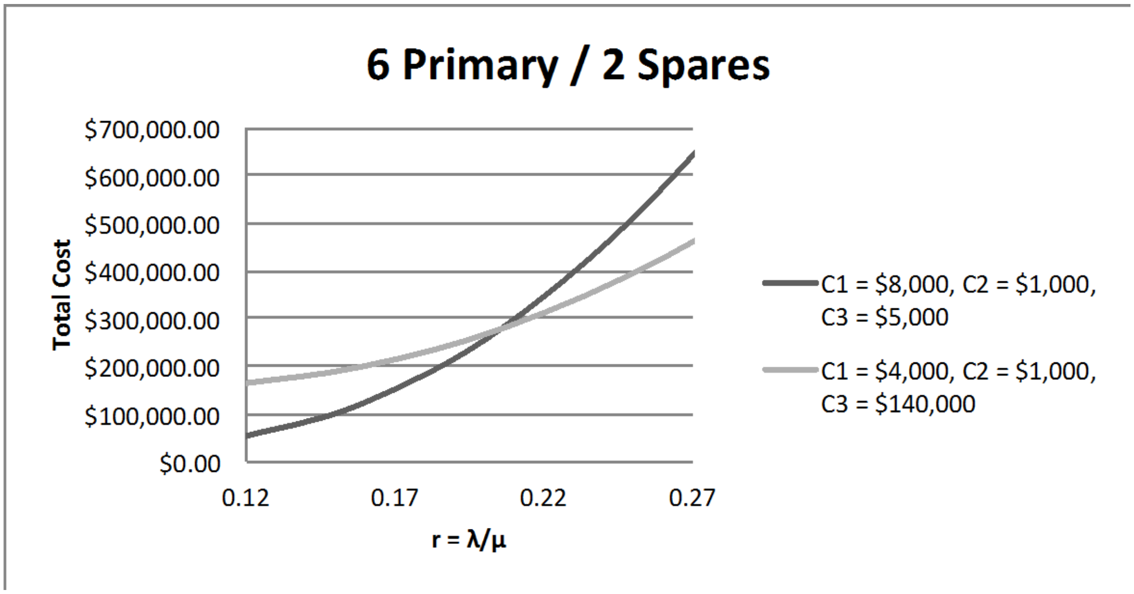

Figure 36: 6 Primary / 2 Spares, Cost of Lost Training Dominated r Region

Comparing the high cost of lost training/less expensive parts cost to the low cost of lost training/high parts cost combinations provides an r value of approximately 0.11 for the 6 Primary / 1 Spare Model (see Figure 37) and comparing a low cost of lost training/low parts cost to the lowest cost of lost training/high parts cost provides an r value of approximately 0.23 (see Figure 38). Therefore, for the 6 Primary / 1 Spare Model, the cost of parts dominates the total cost for r values less than 0.11 and the cost of lost training dominates the total cost for r values greater than 0.23.

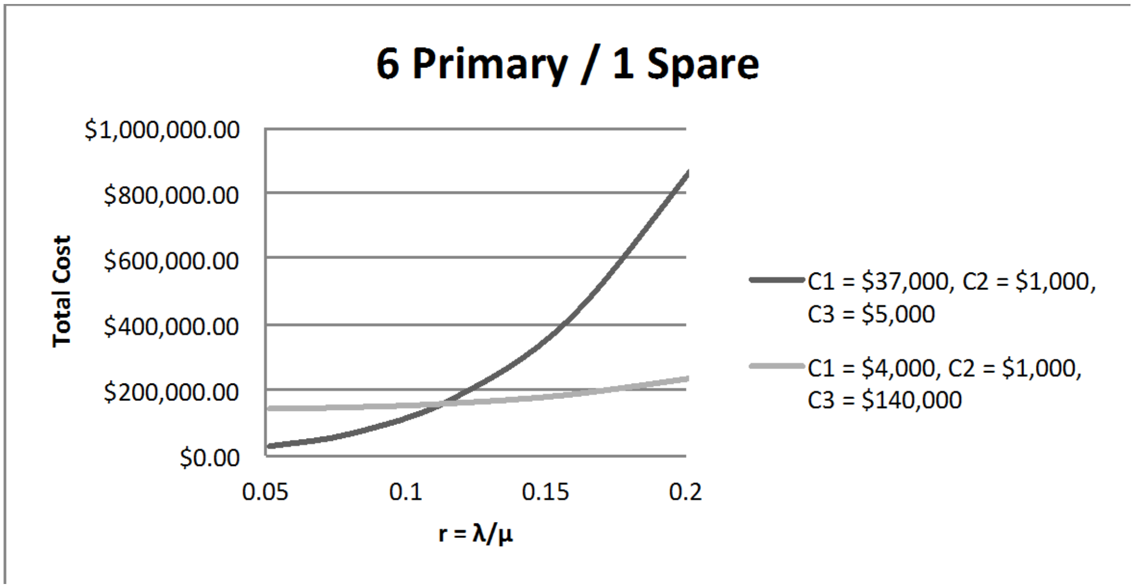

Figure 37: 6 Primary / 1 Spare, Cost of Parts Dominated r Region

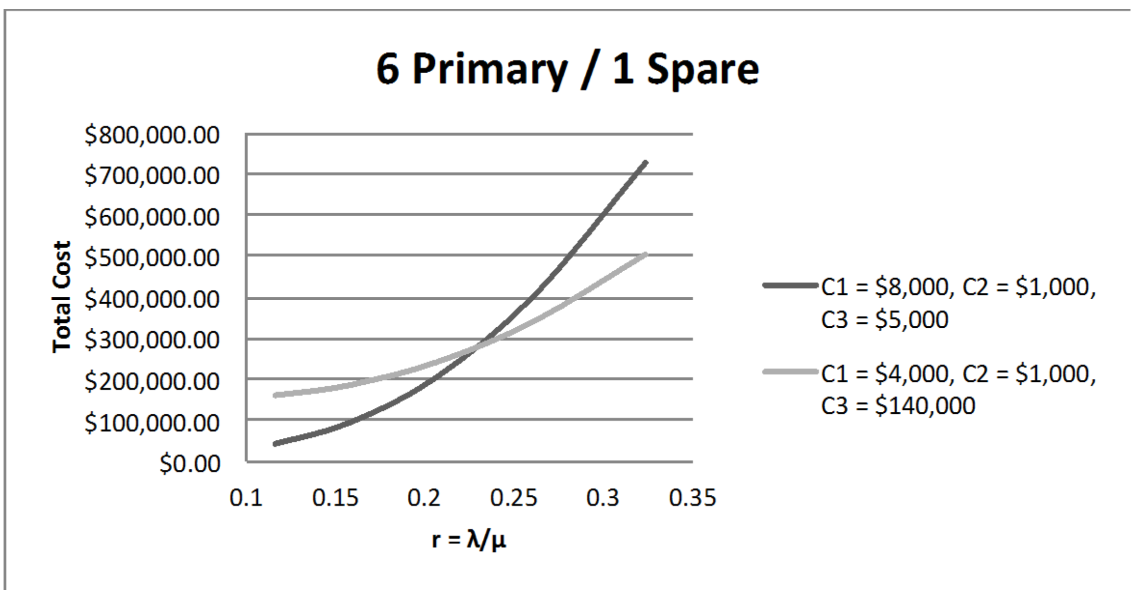

Figure 38: 6 Primary / 1 Spare, Cost of Lost Training Dominated r Region

Comparing the high cost of lost training/less expensive parts cost to the low cost of lost training/high parts cost combinations provides an r value of approximately 0.12 for the 5 Primary / 2 Spares Model (see Figure 39) and comparing a low cost of lost training/low parts cost to the lowest cost of lost training/high parts cost provides an r

value of approximately 0.24 (see Figure 40). Therefore, for the 5 Primary / 2 Spares Model, the cost of parts dominates the total cost for r values less than 0.12 and the cost of lost training dominates the total cost for r values greater than 0.24.

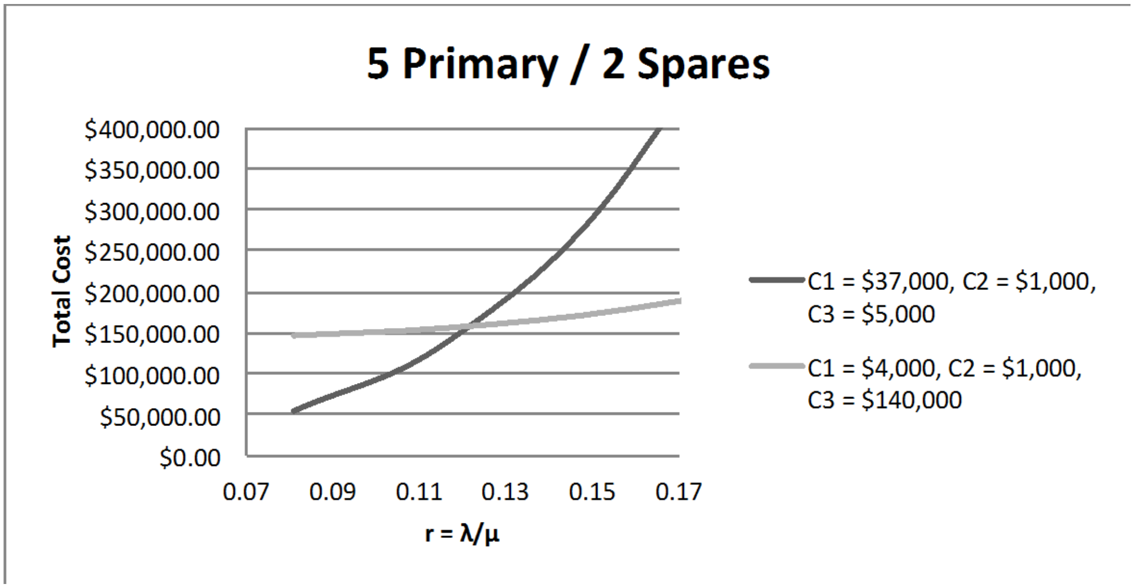

Figure 39: 5 Primary / 2 Spares, Cost of Parts Dominated r Region

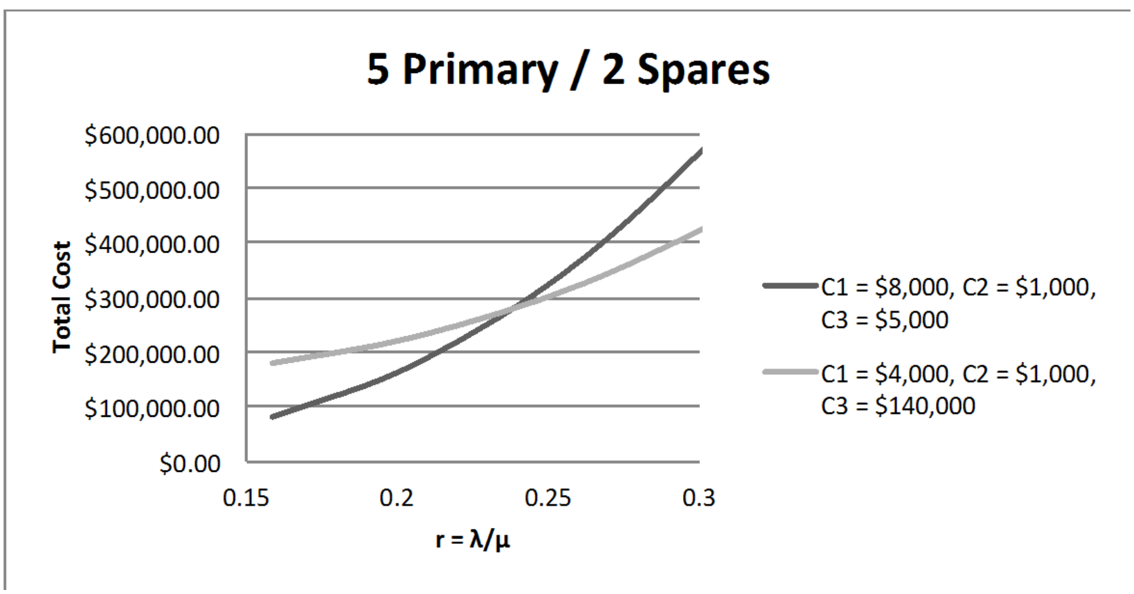

Figure 40: 5 Primary / 2 Spares, Cost of Lost Training Dominated r Region

Comparing the high cost of lost training/less expensive parts cost to the low cost of lost training/high parts cost combinations provides an r value of approximately 0.12 for the 5 Primary / 1 Spare Model (see Figure 41) and comparing a low cost of lost training/low parts cost to the lowest cost of lost training/high parts cost provides an r value of approximately 0.27 (see Figure 42). Therefore, for the 5 Primary / 1 Spare Model, the cost of parts dominates the total cost for r values less than 0.12 and the cost of lost training dominates the total cost for r values greater than 0.27.

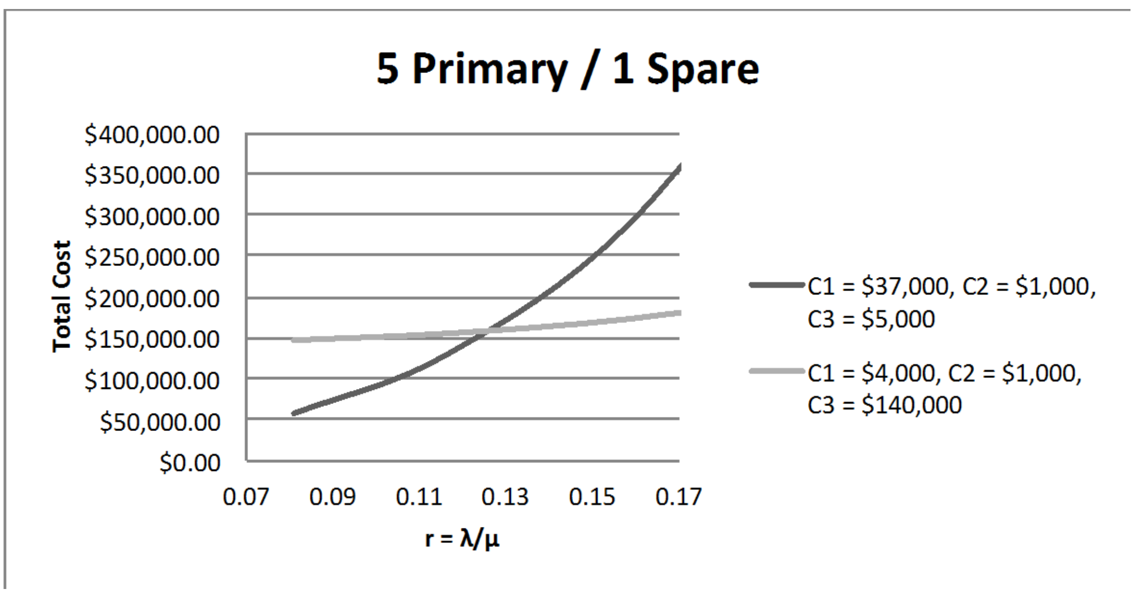

Figure 41: 5 Primary / 1 Spare, Cost of Parts Dominated r Region

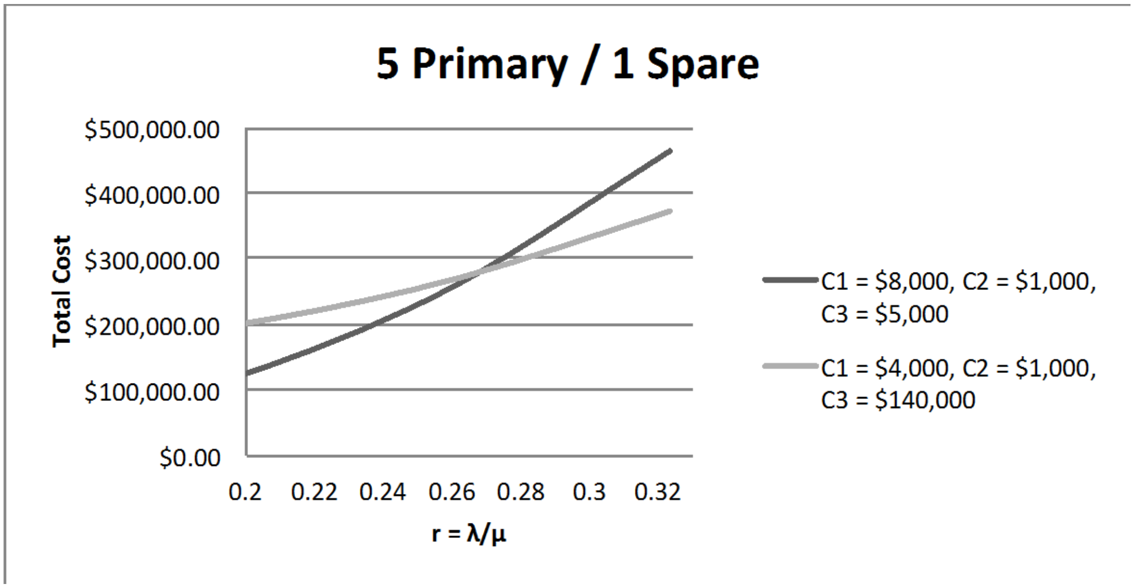

Figure 42: 5 Primary / 1 Spare, Cost of Lost Training Dominated r Region

Comparing the high cost of lost training/less expensive parts cost to the low cost of lost training/high parts cost combinations provides an r value of approximately 0.14 for the 4 Primary / 2 Spares Model (see Figure 43) and comparing a low cost of lost training/low parts cost to the lowest cost of lost training/high parts cost provides an r value of approximately 0.29 (see Figure 44). Therefore, for the 4 Primary / 2 Spares Model, the cost of parts dominates the total cost for r values less than 0.14 and the cost of lost training dominates the total cost for r values greater than 0.29.

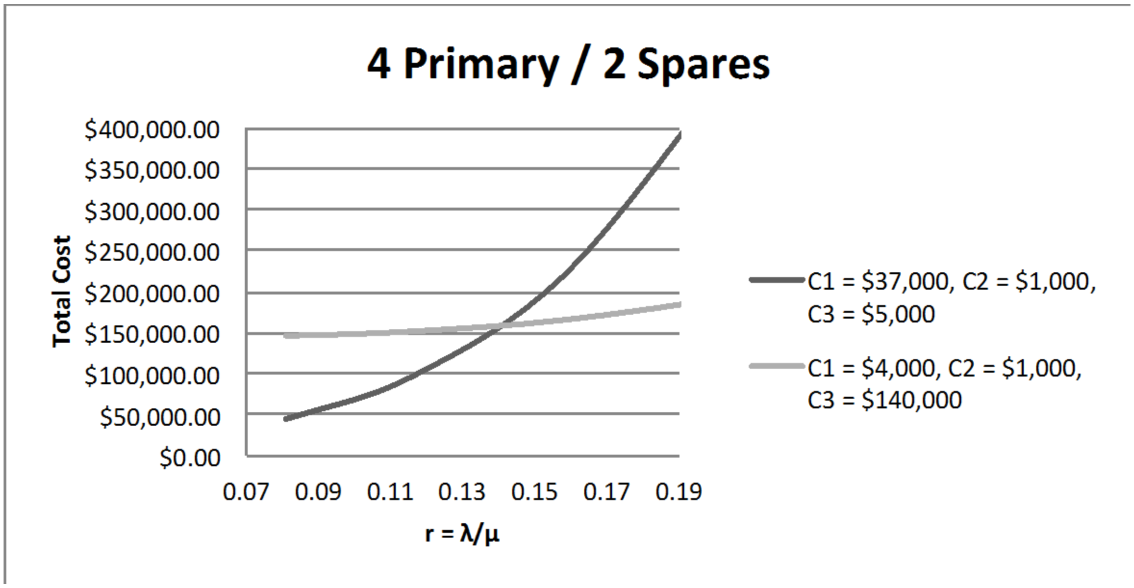

Figure 43: 4 Primary / 2 Spares, Cost of Parts Dominated r Region

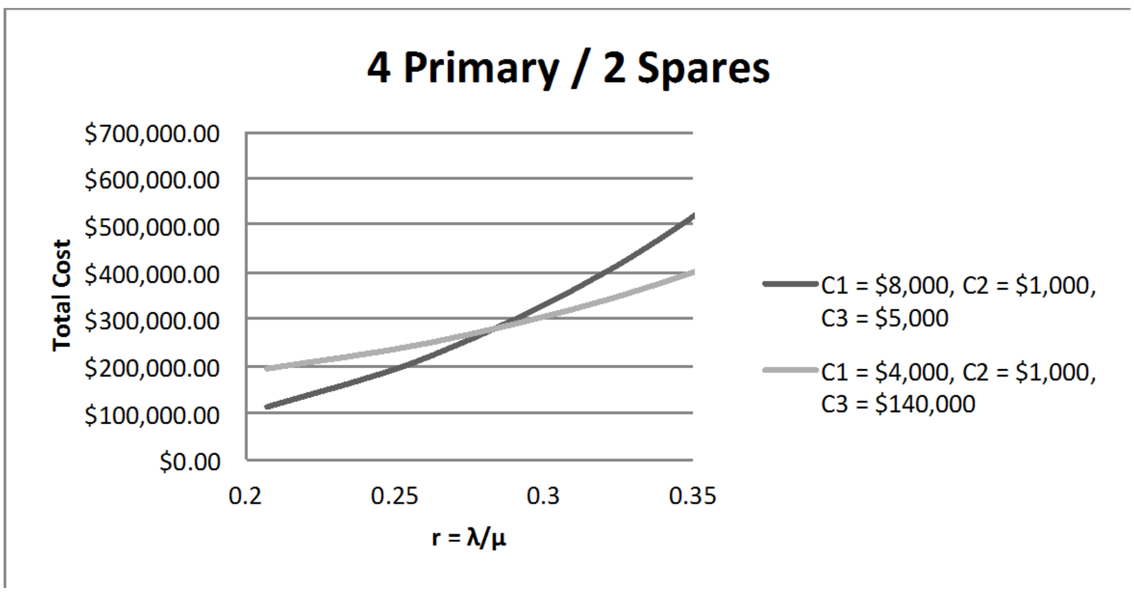

Figure 44: 4 Primary / 2 Spares, Cost of Lost Training Dominated r Region

Comparing the high cost of lost training/less expensive parts cost to the low cost of lost training/high parts cost combinations provides an r value of approximately 0.14 for the 4 Primary / 1 Spare Model (see Figure 45) and comparing a low cost of lost training/low parts cost to the lowest cost of lost training/high parts cost provides an r

value of approximately 0.32 (see Figure 46). Therefore, for the 4 Primary / 1 Spare Model, the cost of parts dominates the total cost for r values less than 0.14 and the cost of lost training dominates the total cost for r values greater than 0.32.

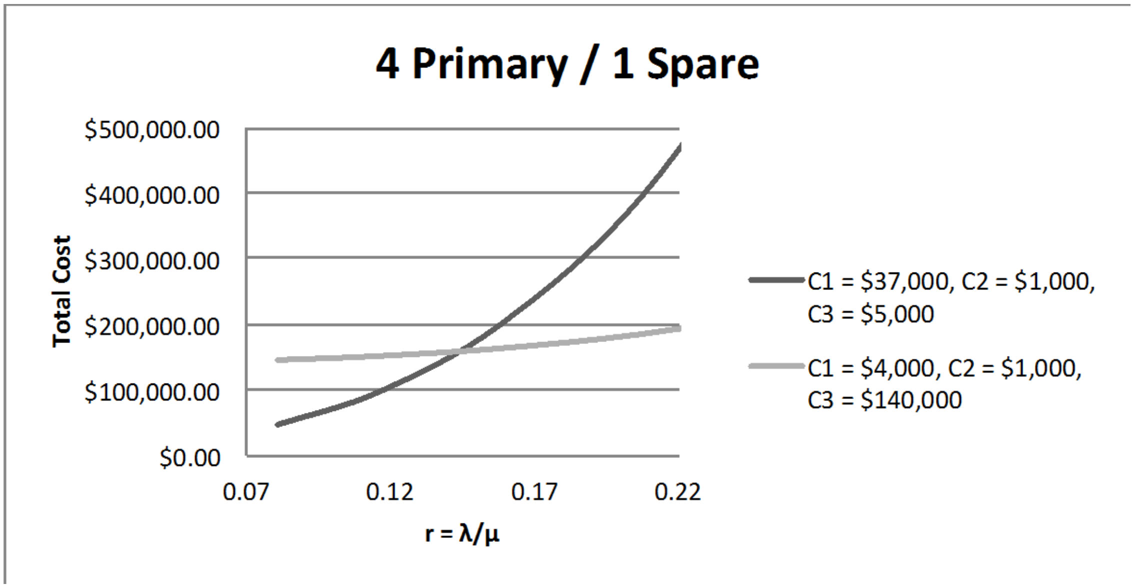

Figure 45: 4 Primary / 1 Spare, Cost of Parts Dominated r Region

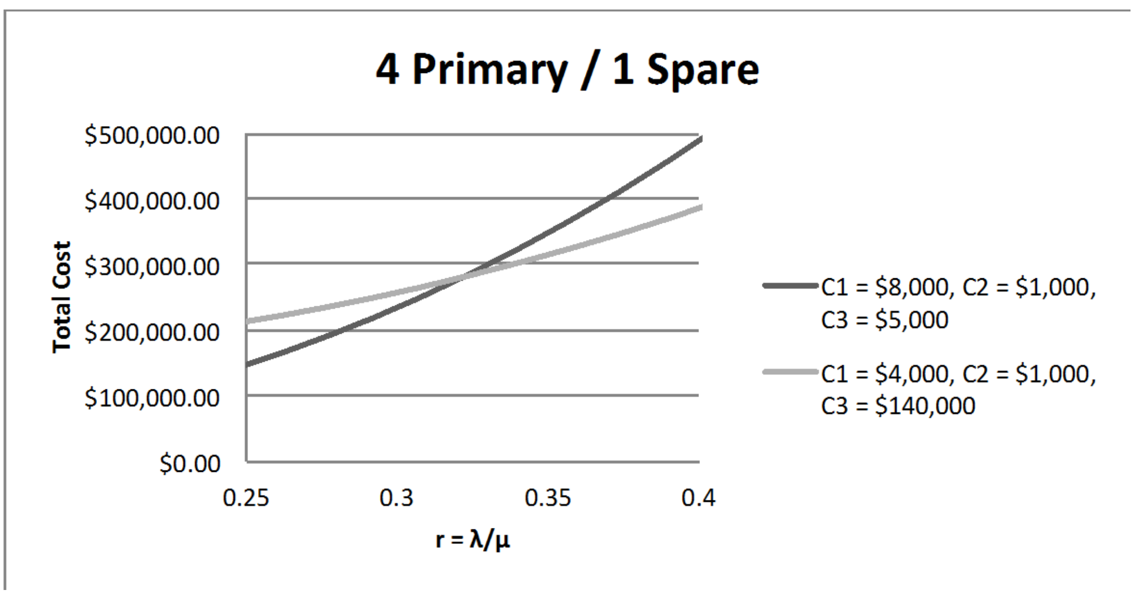

Figure 46: 4 Primary / 1 Spare, Cost of Lost Training Dominated r Region

The crossover r values and their models are consolidated in Table 6.

	Dominating Cost for r Value		
Model	C2 + C3 (1)	C1 & C2 + C3	C1 (2)
6 Primary / 2 Spares	r < 0.11	0.11 < r < 0.20	r > 0.20
6 Primary / 1 Spare	r < 0.11	0.11 < r < 0.23	r > 0.23
5 Primary / 2 Spares	r < 0.12	0.12 < r < 0.24	r > 0.24
5 Primary / 1 Spare	r < 0.12	0.12 < r < 0.27	r > 0.27
4 Primary / 2 Spares	r < 0.14	0.14 < r < 0.29	r > 0.29
4 Primary / 1 Spare	r < 0.14	0.14 < r < 0.32	r > 0.32

(1) Occurs at C1 = $37,000, C2 = $1,000, C3 = $ 5,000 vs. C1 = $4,000, C2 = $1,000, C3 = $140,000
(2) Occurs at C1 = $8,000, C2 = $1,000, C3 = $ 5,000 vs. C1 = $4,000, C2 = $1,000, C3 = $140,000

Table 6: Dominating Cost by r Value & Model

Sample NMC Driver Total Cost Comparison

Comparing actual NMC drivers to determine which one should get limited resources invested on its behalf in order to find a more cost effective approach is fairly straightforward. This section provides a sample comparison of NMC drivers X and Y. X has an arrival rate (λ) of 18/6000 (18 incidences over 6000 flight hours) or 0.003 and service rate (μ) of 18/500 (18 incidences utilizing 500 MX hours to fix) or 0.036 and its resulting r is 0.0833. The related part costs $100,000. Y has an arrival rate (λ) of 0.04 and service rate (μ) of 0.2 and its resulting r is 0.2. The related part costs $2,000. Current flight schedule utilizes 6 primary aircraft and 2 spares daily. The associated performance parameters for both NMC drivers are shown in Table 7. Although Y occurs much more frequently, X has a higher total cost and therefore a better process would be more applicable to X.

NMC Total Cost Comparison		
NMC Driver	X	Y
Total Flight Hours Accrued Before Incident	6000	1000
Number of Incidents	18	40
Total Time from Incident to Return to Flyable Condition	500	200
λ:	0.003	0.04
μ:	0.036	0.2
r	0.0833	0.2
C1	$4,000.00	$4,000.00
C2	$1,000.00	$1,000.00
C3	$100,000.00	$2,000.00
L	0.8729	3.1855
W	6.9847	3.6881
Ws	3.8975	1.0385
Total Cost	$128,284.44	$50,032.12

Table 7: NMC Total Cost Comparison

V. Conclusion

Using queuing methodology to explain the cost associated with individual NMC drivers provides a more systematic approach to determining which driver requires the limited monetary resources available to U.S. Air Force maintenance. Some simple conclusions can be drawn by this analysis.

For low traffic intensities, the cost of parts is the determining factor in the total cost function and at high traffic intensities, the cost of lost training is the determining factor in the total cost function. For r values in between the high and low values, a true determination of C_1, C_2, and C_3 must be made. In general, NMC drivers that keep an airplane on the ground the longest have the highest total cost.

At the end of the day, r values provide a good rule of thumb for individual NMC total cost functions, but that doesn't solve the comparison problem. In order to compare different NMC drivers, the individual arrival rates (λ) and individual service rates with the delay for service factored in (μ) combined with a defined C_1, C_2, and C_3 can be utilized to determine the total cost of each driver. The model used with these inputs is purely a function of the operational requirements and although certain models have lower costs than other models, this should not be a factor in the total cost determination. If, however, a recommendation for model were made, 4 primary and 2 spares model typically has the lowest total cost. The NMC driver with the highest total cost should get the limited resources available. These resources should be used to determine a better solution to the way the NMC driver is currently fixed. A better solution would be a solution that increases the mean time between failures, thereby reducing the arrival rate, or increases the throughput, thereby reducing the likelihood of a line forming for the

service. Throughput increase can be accomplished by decreasing the MX hours needed to accomplish the fix or by finding a cheaper parts solution.

Future research in this area should include a better determination of the cost of lost training and the hourly cost of maintenance. It should also include a way to model the true makeup of Air Force maintenance. This model treats maintenance as a single repairman. In reality, that repairman is most likely qualified to do many types of job. Furthermore, the arrival rates are based on flying hours and the service rates are based on MX hours. Both flying hours and MX hours are schedule based and deserve a closer look. Finally, p_n could be incorporated into the model to capture the cost of service (C_2 and C_3) when a spare is utilized.

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Appendix I

AFI 65-503 Table A19-2

FY 2012

MILITARY ANNUAL STANDARD COMPOSITE PAY

BASED ON PRESIDENT'S BUDGET

GRADE	BASIC PAY*	MEDICARE-ELIGIBLE HEALTH CARE ACCRUAL	RETIRED PAY ACCRUAL	BAH	Subsistence	INCENTIVE SPECIAL PAY	PCS	MISCEL-LANEOUS	TOTAL ANNUAL COMPOSITE RATE	ACCLERATION FACTOR	AMT BILLABLE TO NON-DOD ENTITIES
OFFICER											
O-10	$179,700	$5,580	$63,615	$21,267	$2,755	$8,205	$6,090	$15,581	$302,793	$10,791	$308,004
O-9	$179,700	$5,580	$63,238	$29,513	$2,755	$8,205	$6,090	$15,325	$310,406	$10,791	$315,617
O-8	$161,559	$5,580	$55,412	$24,085	$2,755	$8,205	$6,090	$14,938	$278,624	$10,791	$283,835
O-7	$139,875	$5,580	$47,975	$28,255	$2,755	$8,205	$6,090	$15,169	$253,904	$10,791	$259,115
O-6	$116,962	$5,580	$39,851	$27,750	$2,755	$8,205	$6,090	$14,937	$222,130	$10,791	$227,341
O-5	$94,631	$5,580	$32,243	$26,845	$2,755	$8,205	$6,090	$13,258	$189,607	$10,791	$194,818
O-4	$80,029	$5,580	$27,268	$24,647	$2,755	$8,205	$6,090	$11,985	$166,559	$10,791	$171,770
O-3	$64,527	$5,580	$21,986	$20,995	$2,755	$8,205	$6,090	$10,444	$140,582	$10,791	$145,793
O-2	$49,594	$5,580	$17,011	$17,042	$2,755	$8,205	$6,090	$8,374	$114,651	$10,791	$119,862
O-1	$35,636	$5,580	$12,223	$14,337	$2,755	$8,205	$6,090	$6,828	$91,654	$10,791	$96,865
TOTAL AVERAGE	$71,955	$5,580	$24,538	$22,126	$2,755	$8,205	$6,090	$10,960	$152,209	$10,791	$157,420
CADETS	$11,833				$4,260		$183	$905	$17,181		$17,181
ENLISTED											
E-9	$72,601	$5,580	$24,778	$20,101	$4,084	$1,614	$3,114	$9,394	$141,266	$10,791	$146,477
E-8	$58,939	$5,580	$20,116	$18,894	$4,084	$1,614	$3,114	$8,147	$120,488	$10,791	$125,699
E-7	$50,088	$5,580	$17,095	$18,766	$4,084	$1,614	$3,114	$7,306	$107,647	$10,791	$112,858
E-6	$40,773	$5,580	$13,916	$17,839	$4,084	$1,614	$3,114	$6,417	$93,337	$10,791	$98,548
E-5	$32,671	$5,580	$11,151	$15,656	$4,084	$1,614	$3,114	$5,523	$79,393	$10,791	$84,604
E-4	$25,872	$5,580	$8,874	$11,667	$4,084	$1,614	$3,114	$4,721	$65,526	$10,791	$70,737
E-3	$21,163	$5,580	$7,259	$5,343	$4,084	$1,614	$3,114	$3,837	$51,994	$10,791	$57,205
E-2	$19,776	$5,580	$6,783	$3,278	$4,084	$1,614	$3,114	$3,422	$47,651	$10,791	$52,862
E-1	$16,942	$5,580	$5,811	$1,993	$4,084	$1,614	$3,114	$2,819	$41,957	$10,791	$47,168
TOTAL AVERAGE	$32,344	$5,580	$11,056	$12,966	$4,084	$1,614	$3,114	$5,325	$76,083	$10,791	$81,294

TABLE A19-2 ACTIVE AIR FORCE STANDARD COMPOSITE RATES BY GRADE. Air Force activities can use the above rates to estimate the costs of military personnel (includes activated ANG/ARC).

a. The standard rates are a composite and include the following pay elements: basic pay; retired pay accrual (a percentage of basic pay); basic allowance for housing (BAH); incentive and special pays that include aircrew, hazardous duty, physicians, dentists, nurses, hostile fire, and duty at certain places. It also includes miscellaneous pay such as subsistence, family separation allowance, separation payments, social security tax (employer's contribution), overseas station allowances, death gratuities, reenlistment bonuses, special duty assignment pay, clothing allowances, unemployment compensation and personal money allowances for the O-9 and O-10 pay grades.

b. PCS costs are included as a separate category. They represent a worldwide cost per workyear average. The factors are developed by dividing the officer and enlisted worldwide PCS costs for a given year by the respective officer and enlisted workyears.

c. The rates do not provide for the portion of military personnel benefits financed by other appropriations, such as the cost of government-furnished quarters for personnel residing in family housing or dormitories; the cost of mess attendant contracts for personnel subsisting in military dining facilities; and commissary and exchange benefits subsidized by appropriated funds.

d. The composite rates include the per capita normal cost of Medicare-Eligible Retiree Health Care accruals. This cost must be included when determining the cost of military personnel for budget/management studies, however, the accrual figure may not be included in reimbursements to the Air Force Military Personnel accounts during the year of execution. The amount billable to non-DoD entities excludes the per capita normal cost for Medicare-Eligible Retiree Health Care (MERHC) accruals.

e. Basic pay for these officers is limited to the rate of a basic pay for Level II of the Executive Schedule, which currently is $179,700 per year.

f. Rate are applicable to activated Air Reserve Components under Title 10.

OPR: SAF/FMBOP, DSN 224-5948 or (703) 641-5948

Appendix II

Input

Spreadsheet for model calculation was accomplished in MS Excel. This calculation page uses λ and μ determined by the data input section described in the methodology section.

Spares =	2	Machines =	

Performance parameters from this calculation spreadsheet were output to multiple output pages. The first output page uses baseline λ and μ:

Output 1

Actual Hydro

Run

C1 =	37000
C2 =	1000
C3 =	5000

6 Primary / 2 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.07259299	0.05525288	0.03791276	0.02057265	0.00323254
L =	0.70897396	0.47937164	0.29154976	0.14061683	0.01977875
W =	8.55665763	5.55420909	3.27914533	1.54822966	0.21439956
Ws =	5.16769212	3.81321565	2.55275408	1.35860252	0.21024201
L*W*C1 =	$224,458.56	$98,513.62	$35,373.26	$8,055.16	$156.90
Ws * C2 + C3 =	$10,167.69	$8,813.22	$7,552.75	$6,358.60	$5,210.24
Total Cost =	$234,626.25	$107,326.84	$42,926.01	$14,413.77	$5,367.14

6 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.07259299	0.05525288	0.03791276	0.02057265	0.00323254
L =	0.65579865	0.45656831	0.28455199	0.13957514	0.01977504
W =	9.31047256	6.17202494	3.70204262	1.76478087	0.245084
Ws =	5.93893159	4.38268162	2.93022562	1.55643098	0.24036156
L*W*C1 =	$225,914.43	$104,264.19	$38,976.67	$9,113.82	$179.32
Ws * C2 + C3 =	$10,938.93	$9,382.68	$7,930.23	$6,556.43	$5,240.36
Total Cost =	$236,853.36	$113,646.87	$46,906.90	$15,670.25	$5,419.68

5 Primary / 2 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.07259299	0.05525288	0.03791276	0.02057265	0.00323254
L =	0.54068872	0.37355955	0.23238809	0.11454711	0.01642817
W =	8.78677196	5.88015731	3.56986779	1.72731824	0.24419256
Ws =	5.83309522	4.3277802	2.90763981	1.55077348	0.24024637
L*W*C1 =	$175,783.61	$81,273.79	$30,695.01	$7,320.79	$148.43
Ws * C2 + C3 =	$10,833.10	$9,327.78	$7,907.64	$6,550.77	$5,240.25
Total Cost =	$186,616.71	$90,601.57	$38,602.65	$13,871.57	$5,388.68

5 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.07259299	0.05525288	0.03791276	0.02057265	0.00323254
L =	0.50636525	0.35870054	0.22775448	0.11384303	0.0164256
W =	9.87341341	6.71768243	4.12861517	2.01219486	0.28497321
Ws =	6.85844245	5.08354112	3.4090334	1.81404911	0.28039725
L*W*C1 =	$184,983.48	$89,156.54	$34,791.49	$8,475.75	$173.19
Ws * C2 + C3 =	$11,858.44	$10,083.54	$8,409.03	$6,814.05	$5,280.40
Total Cost =	$196,841.92	$99,240.09	$43,200.53	$15,289.80	$5,453.59

4 Primary / 2 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.07259299	0.05525288	0.03791276	0.02057265	0.00323254
L =	0.39705027	0.28012479	0.17805908	0.0896161	0.01309951
W =	9.25723622	6.3733556	3.97219211	1.9677221	0.28391203
Ws =	6.72463248	5.0137069	3.37993429	1.80661323	0.28024147
L*W*C1 =	$135,996.76	$66,057.39	$26,169.54	$6,524.56	$137.61
Ws * C2 + C3 =	$11,724.63	$10,013.71	$8,379.93	$6,806.61	$5,280.24
Total Cost =	$147,721.39	$76,071.10	$34,549.47	$13,331.18	$5,417.85

4 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.07259299	0.05525288	0.03791276	0.02057265	0.00323254
L =	0.37661593	0.27118632	0.17522761	0.08917729	0.01309787
W =	10.8214466	7.54138418	4.74160277	2.36044948	0.34081509
Ws =	8.14939387	6.06447615	4.07848831	2.17433583	0.33643688
L*W*C1 =	$150,794.58	$75,669.45	$30,741.81	$7,788.44	$165.17
Ws * C2 + C3 =	$13,149.39	$11,064.48	$9,078.49	$7,174.34	$5,336.44
Total Cost =	$163,943.97	$86,733.92	$39,820.30	$14,962.78	$5,501.60

The VBA code to accomplish page Output 1 is:

```
Public Sub Output()
```

```
Dim iDelay As Integer
Dim iIteration As Integer
Dim iColumn As Integer

iDelay = 36
iColumn = 4

For iIteration = 1 To 5

   Sheet10.Range("E8").Value = iDelay
   Sheet10.Range("E4").Value = Sheet10.Range("Q5").Value
   Sheet10.Range("E5").Value = Sheet10.Range("R5").Value

   Sheet11.Cells(5, iColumn) = Sheet10.Range("E78").Value
   Sheet11.Cells(6, iColumn) = Sheet10.Range("I77").Value
   Sheet11.Cells(7, iColumn) = Sheet10.Range("K77").Value
   Sheet11.Cells(8, iColumn) = Sheet10.Range("K86").Value
   Sheet11.Cells(16, iColumn) = Sheet10.Range("E99").Value
   Sheet11.Cells(17, iColumn) = Sheet10.Range("I98").Value
   Sheet11.Cells(18, iColumn) = Sheet10.Range("K98").Value
   Sheet11.Cells(19, iColumn) = Sheet10.Range("K107").Value
   Sheet11.Cells(27, iColumn) = Sheet10.Range("E120").Value
   Sheet11.Cells(28, iColumn) = Sheet10.Range("I119").Value
   Sheet11.Cells(29, iColumn) = Sheet10.Range("K119").Value
   Sheet11.Cells(30, iColumn) = Sheet10.Range("K128").Value
   Sheet11.Cells(38, iColumn) = Sheet10.Range("E141").Value
   Sheet11.Cells(39, iColumn) = Sheet10.Range("I140").Value
   Sheet11.Cells(40, iColumn) = Sheet10.Range("K140").Value
   Sheet11.Cells(41, iColumn) = Sheet10.Range("K149").Value
   Sheet11.Cells(49, iColumn) = Sheet10.Range("E162").Value
   Sheet11.Cells(50, iColumn) = Sheet10.Range("I161").Value
   Sheet11.Cells(51, iColumn) = Sheet10.Range("K161").Value
   Sheet11.Cells(52, iColumn) = Sheet10.Range("K170").Value
   Sheet11.Cells(60, iColumn) = Sheet10.Range("E183").Value
   Sheet11.Cells(61, iColumn) = Sheet10.Range("I182").Value
   Sheet11.Cells(62, iColumn) = Sheet10.Range("K182").Value
   Sheet11.Cells(63, iColumn) = Sheet10.Range("K191").Value

   iDelay = iDelay - 9
   iColumn = iColumn + 1

Next
End Sub
```

Output 2

Output page 2 in MS Excel

10 * λ, 1 * μ

C1 =	37000
C2 =	1000
C3 =	5000

Run

6 Primary / 2 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.72592989	0.552528766	0.379127642	0.205726519	0.03232539
L =	6.621828504	6.187592489	5.351811029	3.29210953	0.23919303
W =	181.056757	97.97765086	40.02551094	8.241639154	0.26697789
Ws =	27.33896172	15.82302965	7.430654682	2.26805994	0.216186
L*W*C1 =	$44,360,291.40	$22,431,093.73	$7,925,731.92	$1,003,898.02	$2,362.79
Ws * C2 + C3 =	$32,338.96	$20,823.03	$12,430.65	$7,268.06	$5,216.19
Total Cost =	$44,392,630.36	$22,451,916.76	$7,938,162.58	$1,011,166.08	$7,578.98

6 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.72592989	0.552528766	0.379127642	0.205726519	0.03232539
L =	5.622663979	5.192091719	4.386538959	2.633783662	0.23494537
W =	153.8956108	82.55808774	33.52280906	7.387431885	0.30256041
Ws =	27.35554519	15.86240745	7.529393962	2.445544826	0.24800654
L*W*C1 =	$32,016,222.37	$15,860,019.06	$5,440,817.00	$719,905.20	$2,630.15
Ws * C2 + C3 =	$32,355.55	$20,862.41	$12,529.39	$7,445.54	$5,248.01
Total Cost =	$32,048,577.91	$15,880,881.46	$5,453,346.39	$727,350.75	$7,878.16

5 Primary / 2 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.72592989	0.552528766	0.379127642	0.205726519	0.03232539
L =	5.619094058	5.179916831	4.335974657	2.449838101	0.19202987
W =	153.4373352	81.8998679	32.71389653	6.922795039	0.29307014
Ws =	27.28482559	15.75630074	7.386482952	2.346680847	0.24644318
L*W*C1 =	$31,900,616.29	$15,696,676.66	$5,248,325.17	$627,509.90	$2,082.29
Ws * C2 + C3 =	$32,284.83	$20,756.30	$12,386.48	$7,346.68	$5,246.44
Total Cost =	$31,932,901.12	$15,717,432.96	$5,260,711.66	$634,856.58	$7,328.74

5 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.72592989	0.552528766	0.379127642	0.205726519	0.03232539
L =	4.623540994	4.197912203	3.428886757	1.950036878	0.18919966
W =	126.9246619	67.45143905	27.35378152	6.508154168	0.33992805
Ws =	27.37297487	15.91364074	7.653407656	2.636512348	0.28873437
L*W*C1 =	$21,713,130.97	$10,476,743.11	$3,470,341.71	$469,572.20	$2,379.63
Ws * C2 + C3 =	$32,372.97	$20,913.64	$12,653.41	$7,636.51	$5,288.73
Total Cost =	$21,745,503.94	$10,497,656.75	$3,482,995.12	$477,208.72	$7,668.36

4 Primary / 2 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.72592989	0.552528766	0.379127642	0.205726519	0.03232539
L =	4.606696604	4.154572416	3.308838039	1.709722957	0.14814769
W =	125.1337854	65.53274644	25.76333836	5.90972997	0.32868526
Ws =	27.04204833	15.53990957	7.312000563	2.488831763	0.28670884
L*W*C1 =	$21,328,775.22	$10,073,640.01	$3,154,128.42	$373,848.04	$1,801.68
Ws * C2 + C3 =	$32,042.05	$20,539.91	$12,312.00	$7,488.83	$5,286.71
Total Cost =	$21,360,817.27	$10,094,179.92	$3,166,440.42	$381,336.87	$7,088.39

4 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.72592989	0.552528766	0.379127642	0.205726519	0.03232539
L =	3.627378218	3.217060989	2.523432218	1.374499577	0.14640784
W =	100.8848588	53.52425073	22.23724407	5.95285388	0.39314726
Ws =	27.44949721	16.08455343	7.945584176	2.945187294	0.34567754
L*W*C1 =	$13,540,058.96	$6,371,058.82	$2,076,224.59	$302,741.22	$2,129.71
Ws * C2 + C3 =	$32,449.50	$21,084.55	$12,945.58	$7,945.19	$5,345.68
Total Cost =	$13,572,508.45	$6,392,143.38	$2,089,170.18	$310,686.41	$7,475.39

VBA code to extract these parameters:

Public Sub OutputTwo()

Dim iDelay As Integer

```
Dim iIteration As Integer
Dim iColumn As Integer

iDelay = 36
iColumn = 4

For iIteration = 1 To 5

   Sheet10.Range("E8").Value = iDelay
   Sheet10.Range("E4").Value = Sheet10.Range("Q14").Value
   Sheet10.Range("E5").Value = Sheet10.Range("R5").Value

   Sheet12.Cells(5, iColumn) = Sheet10.Range("E78").Value
   Sheet12.Cells(6, iColumn) = Sheet10.Range("I77").Value
   Sheet12.Cells(7, iColumn) = Sheet10.Range("K77").Value
   Sheet12.Cells(8, iColumn) = Sheet10.Range("K86").Value
   Sheet12.Cells(16, iColumn) = Sheet10.Range("E99").Value
   Sheet12.Cells(17, iColumn) = Sheet10.Range("I98").Value
   Sheet12.Cells(18, iColumn) = Sheet10.Range("K98").Value
   Sheet12.Cells(19, iColumn) = Sheet10.Range("K107").Value
   Sheet12.Cells(27, iColumn) = Sheet10.Range("E120").Value
   Sheet12.Cells(28, iColumn) = Sheet10.Range("I119").Value
   Sheet12.Cells(29, iColumn) = Sheet10.Range("K119").Value
   Sheet12.Cells(30, iColumn) = Sheet10.Range("K128").Value
   Sheet12.Cells(38, iColumn) = Sheet10.Range("E141").Value
   Sheet12.Cells(39, iColumn) = Sheet10.Range("I140").Value
   Sheet12.Cells(40, iColumn) = Sheet10.Range("K140").Value
   Sheet12.Cells(41, iColumn) = Sheet10.Range("K149").Value
   Sheet12.Cells(49, iColumn) = Sheet10.Range("E162").Value
   Sheet12.Cells(50, iColumn) = Sheet10.Range("I161").Value
   Sheet12.Cells(51, iColumn) = Sheet10.Range("K161").Value
   Sheet12.Cells(52, iColumn) = Sheet10.Range("K170").Value
   Sheet12.Cells(60, iColumn) = Sheet10.Range("E183").Value
   Sheet12.Cells(61, iColumn) = Sheet10.Range("I182").Value
   Sheet12.Cells(62, iColumn) = Sheet10.Range("K182").Value
   Sheet12.Cells(63, iColumn) = Sheet10.Range("K191").Value

   iDelay = iDelay - 9
   iColumn = iColumn + 1

Next
End Sub
```

Output 3

Output page 3 in MS Excel:

1 * λ, 10 * μ

Run

C1 =	37000
C2 =	1000
C3 =	5000

6 Primary / 2 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.0072593	0.00552529	0.00379128	0.00205727	0.00032325
L =	0.04553666	0.03428758	0.02327697	0.01249784	0.00194329
W =	0.49521733	0.37235253	0.25243071	0.13535166	0.02101808
Ws =	0.47366838	0.36001523	0.24669	0.13368106	0.02097732
L*W*C1 =	$834.37	$472.38	$217.41	$62.59	$1.51
Ws * C2 + C3 =	$5,473.67	$5,360.02	$5,246.69	$5,133.68	$5,020.98
Total Cost =	$6,308.04	$5,832.40	$5,464.10	$5,196.27	$5,022.49

6 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.0072593	0.00552529	0.00379128	0.00205727	0.00032325
L =	0.04549375	0.03426883	0.02327097	0.01249689	0.00194329
W =	0.56606479	0.42565059	0.28856255	0.15471432	0.02402147
Ws =	0.54177502	0.41169803	0.28204876	0.15281249	0.02397491
L*W*C1 =	$952.84	$539.70	$248.46	$71.54	$1.73
Ws * C2 + C3 =	$5,541.78	$5,411.70	$5,282.05	$5,152.81	$5,023.97
Total Cost =	$6,494.61	$5,951.40	$5,530.51	$5,224.35	$5,025.70

5 Primary / 2 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.0072593	0.00552529	0.00379128	0.00205727	0.00032325
L =	0.03766206	0.02841085	0.01932256	0.01039322	0.00161889
W =	0.56153104	0.42303364	0.28733488	0.15435414	0.02401261
Ws =	0.5411656	0.41135209	0.28188923	0.1527665	0.0239738
L*W*C1 =	$782.49	$444.69	$205.43	$59.36	$1.44
Ws * C2 + C3 =	$5,541.17	$5,411.35	$5,281.89	$5,152.77	$5,023.97
Total Cost =	$6,323.66	$5,856.05	$5,487.31	$5,212.12	$5,025.41

5 Primary / 1 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.0072593	0.00552529	0.00379128	0.00205727	0.00032325
L =	0.03763254	0.02839792	0.01931841	0.01039257	0.00161888
W =	0.65536364	0.49372338	0.33533042	0.18011683	0.02801576
Ws =	0.63192646	0.48023591	0.32902233	0.17827175	0.02797051
L*W*C1 =	$912.53	$518.77	$239.69	$69.26	$1.68
Ws * C2 + C3 =	$5,631.93	$5,480.24	$5,329.02	$5,178.27	$5,027.97
Total Cost =	$6,544.46	$5,999.00	$5,568.71	$5,247.53	$5,029.65

4 Primary / 2 Spares

	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.0072593	0.00552529	0.00379128	0.00205727	0.00032325
L =	0.02990482	0.0226004	0.01539857	0.00829734	0.00129469
W =	0.64996987	0.49060919	0.33386911	0.179688	0.02800521
Ws =	0.63110849	0.47977013	0.32880682	0.17820941	0.027969
L*W*C1 =	$719.18	$410.25	$190.22	$55.16	$1.34
Ws * C2 + C3 =	$5,631.11	$5,479.77	$5,328.81	$5,178.21	$5,027.97
Total Cost =	$6,350.29	$5,890.02	$5,519.03	$5,233.37	$5,029.31

4 Primary / 1 Spares

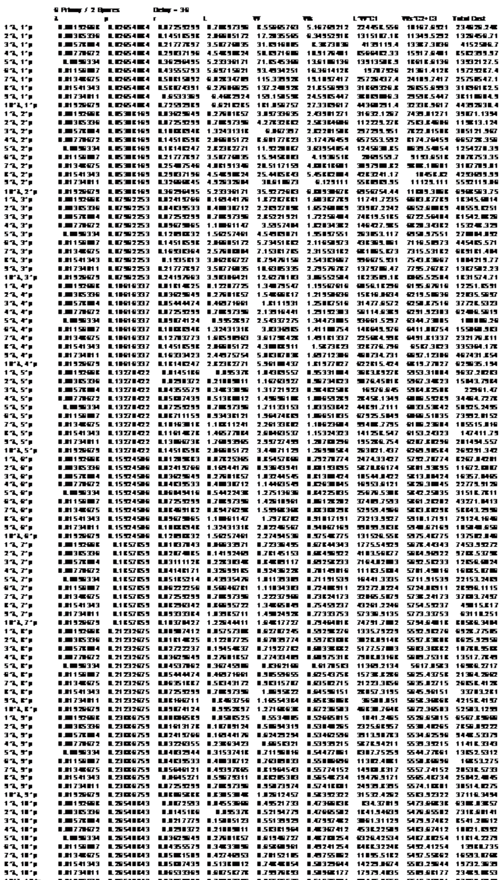
	MX + 36	MX + 27	MX + 18	MX + 9	MX + 0
r = λ/μ =	0.0072593	0.00552529	0.00379128	0.00205727	0.00032325
L =	0.02988611	0.02259219	0.01539593	0.00829692	0.00129469
W =	0.78041666	0.58903257	0.40080309	0.21567803	0.03360767
Ws =	0.75808681	0.57615889	0.39477113	0.21391052	0.03356425
L*W*C1 =	$862.97	$492.38	$228.32	$66.21	$1.61
Ws * C2 + C3 =	$5,758.09	$5,576.16	$5,394.77	$5,213.91	$5,033.56
Total Cost =	$6,621.06	$6,068.54	$5,623.09	$5,280.12	$5,035.17

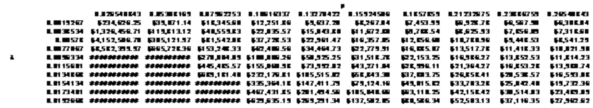
VBA code to extract these parameters:

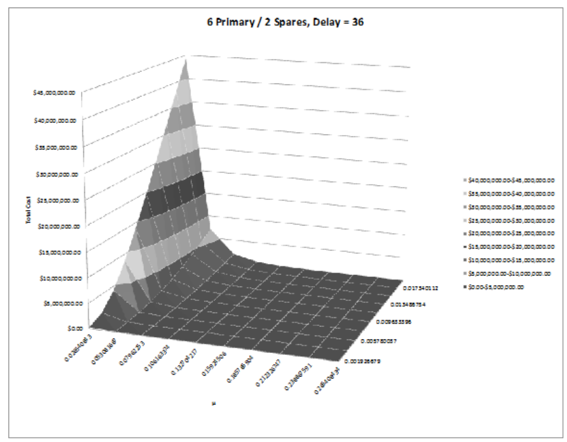
```
Public Sub OutputThree()

Dim iDelay As Integer
Dim iIteration As Integer
Dim iColumn As Integer

iDelay = 36
iColumn = 4

For iIteration = 1 To 5

   Sheet10.Range("E8").Value = iDelay
   Sheet10.Range("E4").Value = Sheet10.Range("Q5").Value
   Sheet10.Range("E5").Value = Sheet10.Range("R14").Value

   Sheet15.Cells(5, iColumn) = Sheet10.Range("E78").Value
   Sheet15.Cells(6, iColumn) = Sheet10.Range("I77").Value
   Sheet15.Cells(7, iColumn) = Sheet10.Range("K77").Value
   Sheet15.Cells(8, iColumn) = Sheet10.Range("K86").Value
   Sheet15.Cells(16, iColumn) = Sheet10.Range("E99").Value
   Sheet15.Cells(17, iColumn) = Sheet10.Range("I98").Value
   Sheet15.Cells(18, iColumn) = Sheet10.Range("K98").Value
   Sheet15.Cells(19, iColumn) = Sheet10.Range("K107").Value
   Sheet15.Cells(27, iColumn) = Sheet10.Range("E120").Value
   Sheet15.Cells(28, iColumn) = Sheet10.Range("I119").Value
   Sheet15.Cells(29, iColumn) = Sheet10.Range("K119").Value
   Sheet15.Cells(30, iColumn) = Sheet10.Range("K128").Value
   Sheet15.Cells(38, iColumn) = Sheet10.Range("E141").Value
   Sheet15.Cells(39, iColumn) = Sheet10.Range("I140").Value
   Sheet15.Cells(40, iColumn) = Sheet10.Range("K140").Value
   Sheet15.Cells(41, iColumn) = Sheet10.Range("K149").Value
   Sheet15.Cells(49, iColumn) = Sheet10.Range("E162").Value
   Sheet15.Cells(50, iColumn) = Sheet10.Range("I161").Value
   Sheet15.Cells(51, iColumn) = Sheet10.Range("K161").Value
   Sheet15.Cells(52, iColumn) = Sheet10.Range("K170").Value
   Sheet15.Cells(60, iColumn) = Sheet10.Range("E183").Value
   Sheet15.Cells(61, iColumn) = Sheet10.Range("I182").Value
   Sheet15.Cells(62, iColumn) = Sheet10.Range("K182").Value
   Sheet15.Cells(63, iColumn) = Sheet10.Range("K191").Value

   iDelay = iDelay - 9
   iColumn = iColumn + 1

Next
End Sub
```

Output 4-9

Output 4 provides a total cost comparison for a range of λ vs. μ by delay. This example from Output 4 is for 6 Primary / 2 Spares and Delay = 36. Output 4 also provides this same information for 0, 9, 18, and 27 hour delays. Output 5, 6, 7, 8, and 9 accomplish the same extraction for the remaining models.







VBA code to extract these parameters:

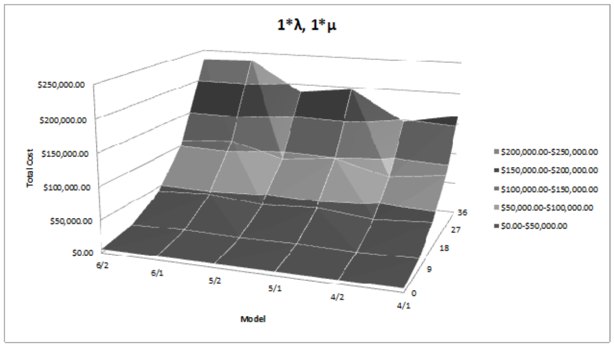
```
Public Sub OutputFour()

Dim iDelay As Integer
Dim iIteration As Integer
Dim iIteration2 As Integer
Dim iIteration3 As Integer
Dim iColumn As Integer
Dim iRow As Integer
Dim iRow2 As Integer
```

```
Dim iRow3 As Integer

iDelay = 36
iColumn = 6
iRow = 5
iRow2 = 5
iRow3 = 4

For iIteration3 = 1 To 5

   Sheet10.Range("E8").Value = iDelay

   For iIteration = 1 To 10

         For iIteration2 = 1 To 10

            Sheet10.Range("E4").Value = Sheet10.Cells(iRow, 17)
            Sheet10.Range("E5").Value = Sheet10.Cells(iRow2, 18)

            Sheet1.Cells(iRow3, iColumn) = Sheet10.Cells(iRow, 17).Value
            Sheet1.Cells(iRow3, iColumn + 1) = Sheet10.Cells(iRow2, 18).Value
            Sheet1.Cells(iRow3, iColumn + 2) = Sheet10.Range("E78").Value
            Sheet1.Cells(iRow3, iColumn + 3) = Sheet10.Range("I77").Value
            Sheet1.Cells(iRow3, iColumn + 4) = Sheet10.Range("K77").Value
            Sheet1.Cells(iRow3, iColumn + 5) = Sheet10.Range("K86").Value

            iRow = iRow + 1
            iRow3 = iRow3 + 1

         Next

      iRow = 5
      iRow2 = iRow2 + 1

   Next

   iDelay = iDelay - 9
   iRow2 = 5
   iRow3 = iRow3 + 4

Next

End Sub
```

Output 10

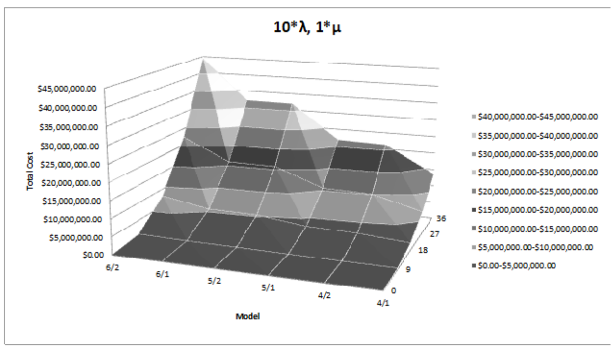
1 * λ, 1 * μ

		Delay				
C1 = 37000		0	9	18	27	36
C2 = 1000	6/2	$5,367.14	$14,413.77	$42,926.01	$107,326.84	$234,626.25
C3 = 5000	6/1	$5,419.68	$15,670.25	$46,906.90	$113,646.87	$236,853.36
Model	5/2	$5,388.68	$13,871.57	$38,602.65	$90,601.57	$186,616.71
	5/1	$5,453.59	$15,289.80	$43,200.53	$99,240.09	$196,841.92
	4/2	$5,417.85	$13,331.18	$34,549.47	$76,071.10	$147,721.39
	4/1	$5,501.60	$14,962.78	$39,820.30	$86,733.92	$163,943.97



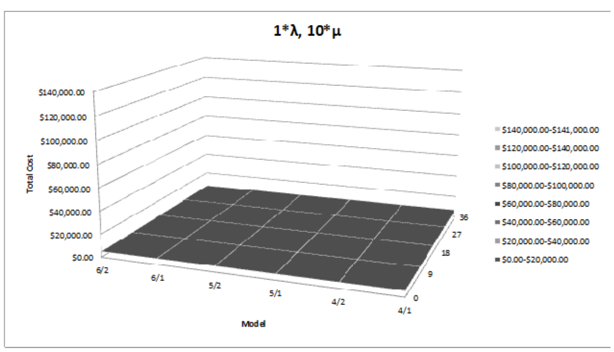
10 * λ, 1 * μ

		Delay				
		0	9	18	27	36
	6/2	$7,578.98	$1,011,166.08	$7,938,162.58	$22,451,916.76	$44,392,630.36
	6/1	$7,878.16	$727,350.75	$5,453,346.39	$15,880,881.46	$32,048,577.91
Model	5/2	$7,328.74	$634,856.58	$5,260,711.66	$15,717,432.96	$31,932,901.12
	5/1	$7,668.36	$477,208.72	$3,482,995.12	$10,497,656.75	$21,745,503.94
	4/2	$7,088.39	$381,336.87	$3,166,440.42	$10,094,179.92	$21,360,817.27
	4/1	$7,475.39	$310,686.41	$2,089,170.18	$6,392,143.38	$13,572,508.45



1 * λ, 10 * μ

		Delay				
		0	9	18	27	36
	6/2	$5,022.49	$5,196.27	$5,464.10	$5,832.40	$6,308.04
	6/1	$5,025.70	$5,224.35	$5,530.51	$5,951.40	$6,494.61
Model	5/2	$5,025.41	$5,212.12	$5,487.31	$5,856.05	$6,323.66
	5/1	$5,029.65	$5,247.53	$5,568.71	$5,999.00	$6,544.46
	4/2	$5,029.31	$5,233.37	$5,519.03	$5,890.02	$6,350.29
	4/1	$5,035.17	$5,280.12	$5,623.09	$6,068.54	$6,621.06



Output 10 provides a comparison of models. The cells are directly referenced to the corresponding data in Output 4-9.

Appendix III

Storyboard:

COST COMPARISON OF B-1B NON-MISSION-CAPABLE DRIVERS USING FINITE SOURCE QUEUEING WITH SPARES

PROBLEM STATEMENT

- The purpose of this research is to compare the total cost associated with an NMC driver with other NMC drivers in order to determine where limited resources are best allocated towards finding a better solution.

RESEARCH OBJECTIVES

- Determine the total cost associated with a generic NMC driver to include cost of lost training, cost per maintenance hour, and parts cost.
- Determine a ratio range for individual cost determination in the total cost function.

COST FUNCTION

- Cost Due to Lost Training = C_1*L*W
- Cost Due to Service = W_s*C_2+C_3
- Total Cost = (C_1*L*W)+(W_s*C_2+C_3)
- 2 classes of variables:
  - C_1, C_2, and C_3 (Estimation / Federal Stock Class)
  - L, W, and W_s (Queueing equations)

COSTS

- C_1 = Cost of Lost Training
  - 4 man crew
  - $4,000 to $37,000 per hour
- C_2 = Cost per Maintenance Man-Hour
  - AFI 65-503
  - E-3: $51,994 → $25/hour
  - E-8: $120,488 → $58/hour
  - Does not include cost of supervision, training, or equipment → conservative approach $1,000/hour
- C_3 = Cost of Part
  - Federal Stock Class (FSC) Identifier
  - A couple cents to over $140,000

Maj Daniel Diehl
Department of Operational Sciences (ENS)

ADVISOR
Dr. Jeffery K. Cochran

RESEARCH SPONSOR
28 Bomb Wing
Ellsworth AFB, SD

$$1)\quad \lambda_n = \begin{cases} M\lambda & (0 \le n < Y) \\ (M-n+Y)\lambda & (Y \le n < Y+M) \\ 0 & (n \ge Y+M) \end{cases} \qquad p_n = \begin{cases} \dfrac{M^n}{n!} r^n p_0 & (0 \le n < c) \\ \dfrac{M^n}{c^{n-c}c!} r^n p_0 & (c \le n < Y) \\ \dfrac{M^Y M!}{(M-n+Y)!\,c^{n-c}c!} r^n p_0 & (Y \le n \le Y+M) \end{cases}$$

1) General Equation
2) Adjusted for 1 server
3) Adjusted for 1 spare
4) Adjusted for 2 spares

$$2)\quad p_n = \begin{cases} p_0 & (n=0) \\ M^n r^n p_0 & (1 \le n < Y) \\ \dfrac{M^Y M!}{(M-n+Y)!} r^n p_0 & (Y \le n \le Y+M) \end{cases}$$

$$3)\quad \lambda_n = \begin{cases} M\lambda & (n=0) \\ (M-n+1)\lambda & (1 \le n < 1+M) \\ 0 & (n \ge 1+M) \end{cases} \qquad p_n = \begin{cases} p_0 & (n=0) \\ \dfrac{M^1 M!}{(M-n+1)!} r^n p_0 & (1 \le n \le 1+M) \end{cases}$$

$$4)\quad \lambda_n = \begin{cases} M\lambda & (0 \le n \le 1) \\ (M-n+2)\lambda & (2 \le n < 2+M) \\ 0 & (n \ge 2+M) \end{cases} \qquad p_n = \begin{cases} p_0 & (n=0) \\ Mrp_0 & (n=1) \\ \dfrac{M^2 M!}{(M-n+2)!} r^n p_0 & (2 \le n \le 2+M) \end{cases}$$

$$\lambda_{eff} = \lambda\left(M - \sum_{n=Y}^{Y+M}(n-Y)p_n\right)$$

$$p_0 = (1 + a_1 + a_2 + \cdots + a_{M+Y})^{-1}$$

$$\boxed{L = p_0 \sum_{n=1}^{M+Y} n\, a_n}$$

$$\boxed{W = \frac{L}{\lambda_{eff}(M+Y-L)}}$$

$$L = L_q + L_s \quad \text{and} \quad L_q = L - \frac{\lambda_{eff}}{\mu}$$

$$\boxed{W = W_q + W_s} \quad \text{and} \quad \boxed{W_q = \frac{L_q}{\lambda_{eff}(M+Y-L)}}$$

NMC Total Cost Comparison

NMC Driver	X	Y
Total Flight Hours Accrued Before Incident	6000	1000
Number of Incidents	18	40
Total Time from Incident to Return to Flyable Condition	500	200
λ:	0.003	0.04
μ:	0.036	0.2
r	0.0833	0.2
C1	$4,000.00	$4,000.00
C2	$1,000.00	$1,000.00
C3	$100,000.00	$2,000.00
L	0.8729	3.1855
W	6.9847	3.6881
Ws	3.8975	1.0385
Total Cost	$128,284.44	$50,032.12

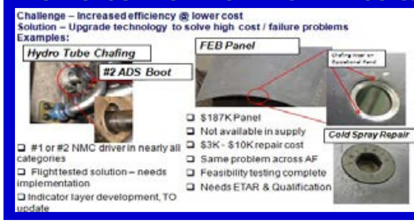
CONCLUSIONS

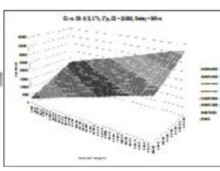
- Goal: Increased efficiency at lower cost
- RoT: Small r → Reduce Parts cost (C_3) or improve MX efficiency (C_2)
- RoT: Large r → New solution to increase time between failure or to allow fix during preventative maintenance (C_1)
- RoT: NMC drivers that keep the airplane on the ground the longest should receive the most attention for determining a better solution
- RoT: 4 Primary, 2 Spares model has lowest associated cost
- In all cases, a better solution is a solution that increases the mean time between failures, thereby reducing the arrival rate, or increases the throughput, thereby reducing the likelihood of a line forming for the service
- Total cost comparison can also be used to look at the potential savings with a proposed solution

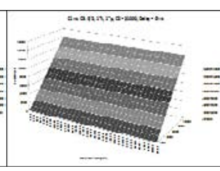
AREAS FOR FUTURE RESEARCH

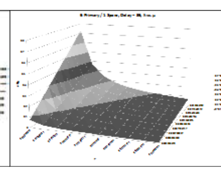
- Validate estimation of C_1 and C_2
- Air Force maintenance may be better modeled with servers greater than 1
- Flying Hours and Maintenance Hours are schedule based
- Incorporate p_n into model to capture C_2 and C_3 when a spare is utilized or when broken systems are found during preventative maintenance

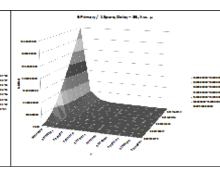
TECHNOLOGY INSERTION INTO MX PROCESS



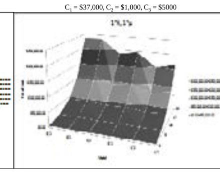




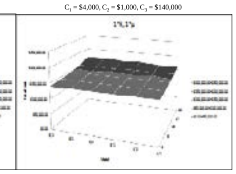




C_1 = $37,000, C_2 = $1,000, C_3 = $5000



C_1 = $4,000, C_2 = $1,000, C_3 = $140,000



Vita

Major Daniel C. Diehl graduated as Valedictorian from Manteo High School, Manteo, North Carolina, in 1995. He earned a Bachelor of Science degree in Biology at the United States Air Force Academy in 1999 as a distinguished graduate. Major Diehl earned a Master's in Business Administration from the University of South Dakota in 2006.

Major Diehl attended Specialized Undergraduate Pilot Training at Columbus AFB, Mississippi where he completed flight training as the Top Flyer. In 2001, Major Diehl was assigned to the 37th Bomb Squadron, Ellsworth AFB, South Dakota. He participated in Operations IRAQI FREEDOM and ENDURING FREEDOM and served as an instructor, mission commander, and earned an "Excellent" rating from the Central Flight Instruction Course. Major Diehl was reassigned to the 28th Bomb Squadron, Dyess AFB, Texas in November 2006. In December 2006, Major Diehl was selected to attend the USAF Weapons School at Nellis AFB, Nevada. He completed the demanding program as the B-1B division Outstanding Graduate along with the Academic and Flying Awards. In July 2008, Major Diehl was reassigned to the 77th Weapons Squadron where he served as an instructor, flight commander, and assistant director of operations. In May 2011, Major Diehl entered the Graduate School of Engineering and Management, Air Force Institute of Technology, Wright-Patterson AFB, Ohio. Upon graduation Major Diehl will attend the School of Advanced Air and Space Studies, Maxwell AFB, Alabama.

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13. SUPPLEMENTARY NOTES

4. ABSTRACT: Maintenance costs and maintenance man-hours have increased dramatically in the last couple of decades in relation to flying hours. These increased costs, combined with shrinking budgets, force the Air Force to streamline maintenance processes and be selective concerning which maintenance processes should receive additional funding. There are many drivers rendering an aircraft non-mission-capable (NMC). This research provides a method to compare the cost associated with any NMC driver with other NMC drivers in order to determine where limited resources are best allocated towards the goal of finding more efficient solutions that also result in reduced cost. The cost model includes lost flying time, maintenance, and parts making it more comprehensive than current methods.

Evaluation of the cost function requires estimating both number of aircraft out of service and time out of service given the behavior of the maintenance system. This is compounded by the fact that there are a small number of aircraft in a flying wing. These aircraft are split between missions and preventative maintenance. Furthermore, due to the increased age of the fleet, the aircraft prepped for missions aren't always mission capable requiring extra aircraft be prepped and ready to step into the lineup making large-number approximations unusable. Instead, a finite source queueing model including spares is incorporated resulting in simple-to-use calculations requiring no special computational resources or training. In fact, as the detailed sensitivity analyses provided in this research demonstrate, the comparison of multiple NMC drivers using the provided cost function is fairly simple provided a reliable estimate of the associated data.

The specific application of the analysis undertaken with this cost/queue formulation is the B-1B bomber. Complete maintenance data from the 28th Maintenance Operations Squadron over 5 years is analyzed to define the parameters of the model and validate its results. Results obtained from this research provide multiple insights into the associated costs of NMC drivers. Certain traffic intensity ranges are dominated by specific costs while cost tradeoffs dominate crossover ranges. Furthermore, expensive parts don't always equate to the NMC driver with the highest cost. More often, NMC drivers that keep an airplane grounded the longest have the highest cost. Finally, recommendations are made among several M primary aircraft and Y spare aircraft configurations for a bomber wing.

15. SUBJECT TERMS
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